National Research Council Canada
Conseil national de recherches Canada

TRAWLER ICING

A COMPILATION OF WORK DONE AT N.R.C.

by

J.R. Stallabrass

Division of Mechanical Engineering

OTTAWA
DECEMBER 1980

Canada

MECHANICAL ENGINEERING REPORT
MD-56
N.R.C. NO. 19372

TRAWLER ICING

A COMPILATION OF WORK DONE AT N.R.C.

GIVRAGE DES CHALUTIERS

COMPILATION DES RECHERCHES EFFECTUÉES AU C.N.R.

by/par

J.R. Stallabrass

T.R. Ringer, Head/Chef
Low Temperature Laboratory/
Laboratoire des basses températures

E.H. Dudgeon
Director/Directeur

SUMMARY

This report collates and reviews the results of an eleven-year project on the icing of fishing trawlers.

Initially the factors causing the icing of ships at sea are presented and some aspects of the physics of the icing process are discussed.

Some simple icing tests on cylinders of various diameters are described. These were made in an icing wind tunnel and demonstrated the effects of air temperature and cylinder size on the resulting ice formations. Later, a number of possible methods for reducing the icing hazard were tested in the wind tunnel and at an outdoor test rig. Of the methods tested the most effective was an inflatable rubber de-icing blanket.

Throughout the project, icing report forms were distributed to vessels operating out of Canadian east coast ports. The data obtained by this means has helped to establish the types of weather systems responsible for icing conditions, the geographical extent of the occurrence of icing, and statistics on the severity of icing encounters in the study area.

Appendices present simplified formulae for the droplet collection efficiency of cylinders and rectangular bodies, the derivation of an analytical expression for the rate of ice build-up on fishing trawlers, and a bibliography of ship icing.

(français au verso)

RÉSUMÉ

Dans le présent rapport, nous compilons et analysons les résultats d'un projet de onze ans sur le givrage des chalutiers.

Dans un premier temps, nous traitons des facteurs à l'origine du givrage des navires en mer et de certains aspects de la physique du processus de givrage.

Nous décrivons quelques essais simples portant sur le givrage de cylindres de différents diamètres. Ces essais ont été menés en soufflerie et ont permis de mettre en évidence les effets de la température de l'air et des dimensions du cylindre sur la formation de la glace résultante. Nous avons par la suite effectué, en soufflerie et sur un gréement d'essai placé à l'extérieur, des essais sur un certain nombre de méthodes susceptibles de réduire le risque de givrage. Parmi ces méthodes, la plus efficace a été l'utilisation d'une couverture de dégivrage gonflable en caoutchouc.

Tout au long du projet, nous avons distribué, aux chalutiers circulant au large des ports de la côte et du pays, des formules de relevé sur le givrage. Les données ainsi obtenues nous ont aidé à déterminer les types de systèmes météorologiques qui créent des conditions de givrage, à évaluer l'étendue géographique où se produit le givrage, et à produire des statistiques sur l'intensité du givrage observé dans la zone étudiée.

Les annexes contiennent des formules simplifiées sur le coefficient de captation des gouttelettes des cylindres et des structures rectangulaires, l'élaboration d'une expression analytique donnant le taux d'accumulation de glace sur les chalutiers et une bibliographie des ouvrages portant sur le givrage des navires.

CONTENTS

CONTENTS (Cont'd)

TABLES

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

APPENDICES

TRAWLER ICING
A COMPILATION OF WORK DONE AT N.R.C.

1.0 INTRODUCTION

As a result of the loss of three Canadian fishing vessels from icing in preceding winters, a research investigation into ship icing was proposed in 1968 jointly by the then Department of Transport, Ship Safety Branch, and the National Research Council.

This project included a preliminary investigation of the icing characteristics of cylindrical objects, and some simple evaluation tests of a number of proposed passive de-icing methods. However, the main thrust of this project has been the collection of data on icing encounters reported by ships operating out of Canadian east coast ports, with the objective of determining the extent and severity of icing conditions in waters off the Canadian east coast.

This report consolidates various reports and papers written during the course of this project which has now been terminated. A bibliography is presented in Appendix C.

2.0 FACTORS CAUSING THE ICING OF SHIPS AT SEA

A perennial hazard faced by the crews of vessels operating in cold northern waters during the winter months is that of icing. This applies particularly to the Canadian east coast fisherman for, in winter, conditions conducive to icing may exist at any time after leaving port, while steaming to or from the fishing grounds or while actually fishing; in fact, his whole trip is likely to lie within a zone of potential icing.

The icing of vessels can result from a variety of causes as indicated by a number of authors (Refs. 1 to 6) as follows:

(a) Supercooled fog (commonly referred to as arctic frost smoke or black frost).

(b) Freezing rain or freezing drizzle.

(c) Falling snow, in particular wet snow.

(d) Freezing sea spray (vessel and/or wind generated).

Of these, the freezing of sea spray on a vessel is the most dangerous cause of icing. The other three causes, all of which result in fresh water ice, are generally not considered serious. However, several writers, particularly Borisenkov (Ref. 3) and Shekhtman (Ref. 8), indicate that the most serious type of icing occurs when one or more of these three lesser causes occurs in combination with freezing sea spray. On the other hand, it has been suggested by Tabata (Ref. 2) that snow and fog should not be emphasized in connection with the icing of ships.

There is general agreement regarding the specific meteorological factors that result in the freezing of sea spray on a ship (Refs. 3, 4, 7, 8). The air temperature must be below the freezing temperature of the sea water (about -1.8°C, but dependent on salinity), the sea temperature lower than about $+6^\circ$C (this limit is less well defined and depends on other factors, particularly air temperature), and the wind speed greater than about 20 knots (Beaufort Force 5), although at lower wind speeds some light icing is likely to occur.

In addition to these factors, which apply also to ocean structures, the degree of icing severity experienced by a vessel is also dependent on the speed and heading of the vessel relative to the wind as well as on the size and lines of the vessel (including freeboard, amount of rigging and other top hamper, etc.).

Combined with the relative wind speed and direction factors, the wave height and frequency also have a bearing on the severity of icing, since these together determine the amount and distribution of water and spray breaking over the vessel. Steep waves of short period result in more spray than long-period waves or swell.

It is apparent from all this that, with so many variables, many of which are not easily measured or characterized, the prediction of the rate of icing on a vessel is no simple task.

3.0 THE ICING PROCESS

The formation of ice on a body results when water impinges on the body in a sub-freezing environment and the rate of loss of heat from the body is such that some or all of the water is frozen before it can run off the body. Clearly, the colder the water, the greater the chance that this will occur. If the impinging water is supercooled (i.e. its temperature is below its equilibrium freezing point) then it is a certainty that ice will be formed providing there is no heat input to the process, such as provided by a heated body or by the kinetic heating of high speed impact between the water and the body. These cases need not concern us in a discussion of the icing process (although a body might be heated as an icing prevention method).

The sea water may be several degrees above its equilibrium freezing point, but due to wave and wind action and to the passage of the vessel, water is detached and some of it strikes the vessel. The decks may be washed by quantities of "green" water which has cooled little and may or may not create much ice. As height increases, the quantity of water becomes less and its degree of subdivision becomes greater, with the result that much of this water will be cooled substantially, and the smaller the drop size the more nearly will its temperature approach that of the ambient air. These drops are likely to remain in a supercooled liquid state* during their flight time from parent sea to striking the vessel's structure. In general then, the greater the height above the sea, the lower the water concentration will be, but a greater proportion of that water will freeze and form ice.

3.1 Drop Deposition

As the size of the water drops decreases, aerodynamic drag forces increase relative to the inertia forces acting on the drops and there is a tendency for the trajectories of the drops to more nearly conform to the streamlines of the air as it is deflected around an object. The larger the object, the greater the deflection for a given drop size and velocity and the lower the proportion of drops that impinge on the object. Thus, the actual impingement or catch rate is less than the potential catch rate assuming straight line motion; the ratio of the actual to potential catch is known as the catch efficiency or collection efficiency. Figure 1 shows the streamlines of air around a cylinder and the manner in which the droplet trajectories are deflected from a straight path. Only those droplets lying between the tangent trajectories impinge on the cylinder, thus the Collection Efficiency, E_m, is defined by the ratio $\frac{S}{D}$.

---

* As the drops cool below their equilibrium freezing temperature they do not immediately freeze but exist in a metastable supercooled liquid state. Pure water can support a maximum supercooling of about 40°C for small droplets of a few microns diameter and about 33°C for volumes of a few cubic centimetres (Ref. 9). However, in nature foreign particles in the water act as freezing nuclei causing freezing to occur at temperatures much warmer than those for homogeneous nucleation; nevertheless significant supercooling still occurs, the most likely freezing temperature being in inverse proportion to the logarithm of droplet size. The effect of salts in solution on the other hand is to lower the nucleation temperature (Ref. 10). The effect of these two opposing phenomena on the supercooling and nucleation of sea water drops is unknown but is obviously of significance to the study of sea spray icing. It has been suggested that below about −18°C the spray is frozen and strikes the ship as small, dry crystals that do not adhere (Ref. 11), however, this is contradicted by Shekhtman (Ref. 8) who cites instances of icing occurring at air temperatures down to −25°C.

The equations of motion of particles in a stream of air appear to have been first developed by Albrecht (Ref. 12) and later applied by Taylor (Ref. 13) to droplets causing icing of aircraft. Values of E_m are not easily calculated; however, Langmuir (Ref. 14) presented droplet trajectory results in graphical form for simple objects such as spheres, cylinders, and flat ribbons in terms of two non-dimensional parameters. The use of graphical results of this sort is not always convenient, particularly in numerical computations, so that in Appendix A (taken from Ref. 15) empirical expressions are presented that permit the direct computation of the collection efficiency of cylinders and flat surfaces over a range of sizes and conditions applicable to the icing of ships and stationary structures, and with sufficient accuracy in view of present uncertainties with regard to defining the spray parameters.

3.2 Heat Balance

When the supercooled drops strike the cold obstacle, it acts as a nucleating agent to initiate freezing, so that, depending on the initial supercooling of the impinging water and the various heat losses and gains at the icing surface (Refs. 16,17) some or all of the impinging water freezes in its immediate area of impingement. The proportion that does actually freeze on impact is called the freezing fraction, n, while the remaining fraction (1−n) flows away from its impingement zone under the influence of gravity or of aerodynamic forces; some of this run-off will flow over areas of greater heat loss where further freezing will occur while some may actually flow or be blown completely off the surface subject to impingement.

The freezing fraction and hence the rate of icing on the obstacle is given by the solution of the heat balance equation, which, if only the primary heat transfer processes acting at the icing surface are taken into consideration (i.e. ignoring heat transfer due to radiation and kinetic and viscous heating which are negligible in this application), may be expressed by:

$$q_f + q_w + q_c + q_e + q_a = 0 \qquad (1)$$

where q_f = latent heat of freezing a certain fraction, n, of the impinging water,

q_w = heating (or cooling) of the impinging water to the equilibrium surface temperature,

q_c = heat transfer by convection to the surrounding air,

q_e = heat transfer by evaporation to the surrounding air,

q_a = heat conducted to or from the icing surface through the underlying structure.

The fraction of the impinging water that freezes decreases both as the temperature increases and as the water concentration increases. The excess water will run off or be blown off the surface, and the mass of ice forming on the obstacle in time, t, is

$$M_i = nM_w = nE_m\,VAwt \qquad (2)$$

where n = freezing fraction

M_w = mass of water impinging on obstacle in time, t

E_m = collection efficiency

V = velocity of air relative to obstacle

A = projected frontal area of obstacle

w = mass of water droplets in unit volume of air (liquid water content).

As the ice forms on the obstacle, the shape presented to the flow of droplets is modified, and the projected frontal area may increase in size. Thus in Equation (2), the quantities n, E_m, and A may all change with time, so that the instantaneous icing rate, $R_i = dM_i/dt$, also becomes a function of time.

If, in Equation (2), A is considered a constant, equal to the frontal area of the ice-free obstacle, then it is possible for E_m and even the Icing Efficiency, $N = nE_m$, to assume values greater than unity if the frontal area of the iced obstacle exceeds the ice-free area A.

The above discussion has looked at the gross or overall icing rate on an object, and where, in Equation (2), the factors n and E_m are the effective or total freezing fractions and collection efficiency for the object as a whole. No information is forthcoming from such considerations on the local growth rate of ice on different parts of the object, and hence on the overall shape of the ice deposit, except in a rather empirical way (Ref. 18).

Determination of local growth rates requires a knowledge of the factors relating to the local convective heat transfer and to the local collection efficiency. Such factors are complex and are far from understood, except perhaps for the simple case of a cylinder for which an attempt (Ref. 19) has been made to numerically model the local icing rate and so predict ice shapes on a cylinder.

4.0 ICING TESTS ON CYLINDERS

As an introduction to the National Research Council's programme of ship icing research, a series of tests was made in an icing wind tunnel (1.37 m square test section) to study the ice formation and rate of growth on cylinders of various diameters. These tests are described fully in Reference 17, and their salient details are presented here.

Five cylinders, 3.8 cm (1½ in.), 7.6 cm (3 in.), 15.2 cm (6 in.), 30.5 cm (12 in.), and 45.7 cm (18 in.) in diameter were used, and one-hour tests were run on each cylinder in both a horizontal and vertical orientation. A wind speed of 43 knots (Beaufort Force 9) was used throughout and each test was repeated at two temperatures (about -14°C and about -7°C). The water sprays were set to give a water concentration in the air of 3.2 g/m^3 with an effective drop diameter of about 0.2 mm. In the light of the paucity of quantitative data on sea spray conditions, these values were chosen rather intuitively within the capabilities of the test facility, but were considered to result in fairly representative icing conditions. One area where conditions where clearly not representative was that fresh water was used rather than sea water.

Typical ice deposits are shown in Figures 2 and 3, and representative shapes are sketched in Figure 4. The effect of greater blow-off and run-off of water at higher temperatures is evident in a smaller ice accretion than at lower temperature, and the effect of gravity results in an asymmetrical formation and icicles on the horizontal cylinders, and a variation of thickness with height on the vertical cylinders.

In analyzing the results, the concept of Icing Efficiency was used (see Section 3.2 above), but in the form of a one-hour icing efficiency, defined as:

$$N_{1h} = \frac{M_1}{VAw} \qquad (3)$$

where M_1 = mass of ice formed in one hour.

The ice deposits were weighed at the end of each 1-hour run and the 1-hour icing efficiency determined. In spite of the difference in the shape of the ice accretions on horizontal and vertical cylinders (as a result of gravity affecting the run-off), no significant difference in icing efficiency was apparent. It was therefore possible to combine the results from both orientations as in Figures 5 and 6, which show the effect of temperature and of cylinder diameter on the 1-hour icing efficiency.

No great significance should be read into the actual rates of icing of the test cylinders, since their relationship to rates of icing at sea is unknown. However, the icing efficiencies derived from these tests, and presented in Figures 5 and 6, are considered to give a useful guide to the fraction of water that actually freezes on rails, masts, lines, etc. over an extended period of time. As noted in Reference 20, "there is virtually no knowledge as to the rate at which spray strikes the exposed surfaces of a ship or of the percentage that freezes". These remarks still apply some 20 years later; however, these results provide some indication of the percentage of spray that may freeze.

The manner in which the icing efficiency increases with decreasing cylinder size, even to values greatly in exeess of 100 percent for small diameter cylinders (Fig. 6), demonstrates very forcefully the absolute necessity for keeping the number of rails, stays, etc. to a minimum, and that, where it is not possible to dispense with them completely, one larger diameter strut should be made to do the job of several smaller ones. It was found that a 12-fold increase in the basic cylinder diameter from 3.8 cm to 45.7 cm resulted in only a 3-fold increase in the mass of ice collected.

It was noticeable that the ice thickness was not significantly affected by the cylinder diameter, but only by the temperature. On the other hand, the width of the ice accretion (dimension A, Fig. 4) was affected by cylinder diameter as well as temperature, and it is this dependence on cylinder diameter that is reflected in the icing efficiency. Figure 7 demonstrates the effects of temperature on ice thickness, and of cylinder diameter on the ice width expressed as the ratio of width to cylinder diameter.

The fact that the ice thickness appears to be independent of cylinder diameter (a relationship that does not apply when all the water freezes in its area of impingement) leads to the speculation that, for sea spray ice, the rate of ice growth might give an approximate measure of the spray concentration providing the air temperature and velocity are known. Tests at other water concentrations and speeds are required to ascertain the reliability of such a measure.

The main findings and conclusions from these tests are:

1. The dependence of the icing efficiency on the cylinder diameter and on the air temperature was demonstrated; the icing efficiency being shown to increase with both decreasing diameter and decreasing temperature.

2. It was shown, for the conditions of the tests, that the ice thickness is a function of the temperature, but is independent of the cylinder diameter.

3. The width of the ice accretion is a function of both temperature and cylinder diameter, such that for small diameter cylinders the ice width may grow to many times the cylinder diameter.

4. The results clearly indicate the necessity for reducing rigging, spars, etc. to a minimum as one very necessary measure for diminishing the hazard of icing at sea.

5.0 METHODS OF REDUCING THE ICING HAZARD

One method of reducing the icing hazard was demonstrated in the tests just described, that is that the number of small scale collectors such as rigging and railings, and top hamper generally, should be reduced to a minimum and where complete elimination is not feasible one larger scale component should be made to serve the function of several small scale ones. This has been recognized for a considerable time (Ref. 11), but that it has not always been fully taken to heart would seem to be evident from some of the discussion in the final report of a British inquiry into trawler safety (Ref. 21).

Unless a vessel can completely avoid icing conditions, some means of combatting the ice are necessary. Methods may be subdivided into two categories, de-icing and anti-icing. Certain de-icing methods require the active intervention of crew members on deck; these include such methods as the use of steam or water hoses as well as the traditional use of mallets and axes. Conditions on deck at these times are particularly hazardous, and become completely impossible when icing conditions are the most severe and de-icing is the most necessary. Also such methods are not amenable to the de-icing of the upper parts of superstructure and rigging where the added weight of ice contributes most to the loss of stability. Preferred methods therefore should preclude the use of crew on deck and so must be of an automatic or semi-automatic nature. Recent proposals or developments include the use of plastic foam as a passive de-icer (Refs. 22, 23), inflatable rubber de-icer blankets (Ref. 24), and an electrical impulse method (Ref. 25). The cost factor seems to militate against the extensive use of electrical heating (Ref. 26) for de-icing.

Tests at NRC (described in Ref. 27 and summarized below) have shown the remarkable effectiveness of the inflatable rubber de-icer on both cylindrical and flat surfaces. Little is known about the Russian electro-impulse system, but if the claims made for it are valid, it might well be effective for the de-icing of large flat metal surfaces.

Anti-icing methods, in which ice is prevented from forming, may be either chemical or thermal. Chemical methods imply basically the use of freezing point depressant chemicals applied at the surface to be protected, although they may be extended to include materials to which ice has negligible adhesive strength. The major problem in the use of freezing point depressants (i.e. glycols and alcohols) is that of uniformly distributing the fluid over the surface. Materials promoting low ice adhesion are theoretically of two types, fluid and solid, the fluid type being typically a silicone oil which prevents ice from adhering to the underlying solid substrate; such a method although resulting in extremely low adhesion (Refs. 28, 29, 30) is perhaps only practical for moderately small mechanical devices on which an oil film can be maintained so as to prevent the mechanism from being jammed by ice. A solid material to which ice will not adhere is a dream not yet realized, and probably unrealizable. Certain fluoro-carbon polymers do display a reduced ice adhesion of about 15 kN/m^2 (20 psi) in shear, but this is still far in excess of the approximate 1 kN/m^2 necessary to promote ready ice release. Certain flexible silicone coatings have shown low values (about 3.5 kN/m^2) on initial ice release, but this deteriorates on subsequent releases and, in addition, problems of ultraviolet degradation and low abrasion resistance currently preclude these materials from practical consideration.

Thermal anti-icing methods are perhaps rather more attractive than chemical ones. Large scale electrical heating is perhaps prohibitively expensive; however, for small items it may provide certain conveniences, a particular case in point being the use of an electrically conducting transparent layer deposited on glass and used for heating bridge windows (Ref. 31, Fig. 41). It seems likely that waste heat from the vessels' main engines could be employed to good purpose, either to heat components such as the mast, etc. directly, or perhaps indirectly by such means as a convective thermosyphon as described by Lock (Ref. 32), or a two-phase thermosyphon (Ref. 33), the action of which is demonstrated in Figure 8. The two-phase thermosyphon has the advantage of higher heat transfer rates and of remote siting of the heat exchanger and boiler section as long as the vapour transport and liquid return are unobstructed. The working fluid could be ammonia, but R21 would be more suited to the temperatures involved since the pressures in the system would then be close to atmospheric and pressure vessel requirements could be less stringent. Tests at NRC have demonstrated the anti-icing effectiveness of such a system when applied to simulated masts and handrails.

5.1 Tests Made at NRC

Evaluation tests (described in detail in Ref. 27) were made on a number of methods proposed for reducing the hazard of superstructure icing on ships at sea. The tests were made under simulated icing conditions, either in the 1.37 m icing wind tunnel, or at an outdoor test site using natural low temperatures in the wintertime. This site is shown in Figure 9. Ten panels 1.2 m $\times$ 0.9 m were attached to a vertical frame of approximately 2.5 m $\times$ 4.6m. Various methods of de-icing were mounted on or applied to the panels. Two cables (a parallel filament rope and a steel cable) were strung diagonally forward and down from the two upper corners of the frame. To augment the prevailing wind a fan was used and on its front face spray nozzles were mounted to produce the icing spray. In both the wind tunnel and outdoor facility, fresh (tap) water was used to produce the icing conditions.

The methods tested were all de-icing methods, that is to say they were all concerned with the removal of the ice after it had formed on various structures, rather than with the prevention of its formation. The specific methods employed were:

1. Pneumatic de-icer as applied to a mast
2. Plastic foam as applied to a mast
3. Plastic foam with rubber surface as applied to a mast
4. Pneumatic de-icer as applied to a bulkhead, such as a bridge front
5. Plastic foam as applied to a bulkhead
6. Plastic foam with rubber surface as applied to a bulkhead
7. Paint and varnish on a wooden bulkhead
8. The distribution of a freezing point depressant (ethylene glycol) over a bulkhead
9. Parallel filament rope for use as stays.

5.1.1 Pneumatic De-icer

A pneumatic de-icer is essentially a tube or series of tubes built into a rubber mat, such that when the tubes are inflated with air they expand and the mat surface heaves and stretches, and in so doing breaks down the adhesion of the ice to the mat surface. Such pneumatic de-icer mats have long been used for de-icing the leading edges of aircraft wings, and recently their application has been extended to marine use. In this application, their use has been proposed for the de-icing of masts and stays, bridge fronts, radar scanners, and liferaft stowages (see, for instance, Ref. 34 or 35).

These tests constitute an independent evaluation of their effectiveness in de-icing masts and flat surfaces. The test specimen was a short length of mast de-icer, 122 cm long and 91 cm wide, suitable for attachment to a 30.5 cm diameter mast. Details are given in Figure 10. The same de-icer was used both for mast de-icing tests in the wind tunnel and, when mounted on a flat surface, for bridge front de-icing tests at the outdoor test stand.

Six tests were made in the wind tunnel on the pneumatic de-icer installed on a 30.5 cm diameter cylinder, 137 cm long, to represent a short length of mast. The de-icer was not bonded to the cylinder, but was laced onto it in the manner shown in Figure 11. The cylinder was mounted in the tunnel in such a way that it could be oscillated about its normal position through ±180°; in this way ice could be built completely around the mast, a situation that might occur should a vessel change course a number of times during an icing encounter. Thus it was possible to see whether there was any change in the de-icer's performance between complete and incomplete encapsulation of the mast in ice. Quite low temperatures (−9 to −23°C) and a high water concentration (3.2 g/m^3) were used for these tests in order that the de-icer be subjected to a severe test.

Only two of the wind tunnel mast tests will be described here. In the first, at −23°C, the mast was exposed to the icing condition for nearly two hours during which time it was rotated ±180° to produce an ice coating uniformly thick around the whole circumference. The radial thickness of the ice at mid-height was about 13 cm on the peaks and 10 cm in the valleys of the rough ice formation (Fig. 12). A further five minutes were allowed to elapse after the sprays were cut off to allow all water on the surface to freeze and some cooling of the ice to occur. One inflation of the de-icer with an air pressure of 100 kPa (15 psi) broke this thickness of fully encapsulating ice cleanly and decisively, as Figure 12 shows.

The second test to be described was at a high temperature, −10°C, and for a duration of only 45 minutes. Because of the higher temperature, the water flowed on the ice surface to a greater extent than on the earlier test. The mast was not rotated for this test and so a rather flat-faced accretion resulted (Fig. 13), being about 4 cm thick at the centre front, but increasing to 9 cm thickness at 45° on either side, and tapering off to nothing at about ±100°. An air pressure of 70 kPa on the de-icer shed this ice cleanly with a single inflation.

Eight tests were made at the outdoor test site on the pneumatic de-icer configured as a bulkhead de-icer. The de-icer was mounted flat on one of the 1.2m X 0.9m panels by clamping to the panel the bars that passed through the attachment ferrules down each side of the de-icer. The de-icer was not bonded to the panel so as to permit the required deformation when the inflation air pressure was applied.

Because of the variability of wind direction, intensity, and gustiness, even when augmented by the fan, it was not possible to assess an effective wind velocity for each run; it was, however, generally in the order of 10 m/s (20 kt). For this reason, and because throughout these tests alterations were made in the water spray system to improve the spray distribution over the test panels, the spray concentration was highly variable from run to run. Since these tests were very qualitative in nature, it was felt that these deficiencies were not of great consequence as long as the ice formation produced appeared reasonably characteristic of shipboard icing.

Again only representative tests will be described. In one, the de-icer was mounted on the upper centre panel. About 10 cm of ice was allowed to form at a temperature of -15°C, and a long overnight cold soak at -19°C was allowed before de-icing was attempted. Thus an abnormally severe test was given the de-icer, requiring more than one inflation. The first inflation cracked the ice on the de-icer, but it remained anchored around the edges and did not shed. A second inflation caused a small amount of ice to break away (Fig. 14b, c) but not until the third inflation was the bulk of the ice dislodged (Fig. 14d). Since the ice was anchored at the edges, and particularly at the top where the de-icer tended to sag away from the steel panel behind, there seems little doubt, had the de-icer been much larger and had it been subjected to the buffeting experienced at sea, that the ice would have shed on the first inflation.

In other tests, two pneumatic de-icers were used, one either side of the upper centre panel onto which was bonded rubber-faced plastic foam. It was thought that the simultaneous inflation of the two de-icers might also remove the ice from the panel between. Three tests were made with this arrangement at de-icing temperatures of -12°C, -8°C and -3°C. At -12°C, ice 4 cm thick was shed cleanly from one de-icer while ice on the other de-icer remained anchored along the top and sides, although being detached from the active surface of the de-icer (Fig. 15). At -8°C ice shed cleanly from both de-icers, but only at -3°C when the ice was rather wet and rotten was the desired result of removing the ice from the intervening rubber-covered panel achieved.

5.1.2 Plastic Foam

As a result of Japanese sea-going tests, mats of plastic foam applied to the hull, bridge front, breakwaters, deck, etc. are reported to be "effective in the prevention of icing, and furthermore make ice removal extremely easy" (Ref. 22).

It was known, before Reference 22 was available, that foamed plastic was being experimented with in Japan, but it was not clear exactly how it functioned as an ice release mechanism, nor the precise materials used. However, some foamed polyethylene sheet was obtained for experimental use. This material was 10 mm thick and had a specific gravity of 0.05.

This plastic foam sheeting was tested both in the wind tunnel on a 30 cm diameter steel cylinder representing a mast, and on flat steel plates on the outdoor test stand. In both instances the foam was bonded onto the steel substrate using a rubber-based adhesive. Tests were made both on the bare plastic foam and with a 0.8 mm thick sheet of neoprene rubber cemented to the outer surface.

Two test runs were made in the wind tunnel on the bare plastic foam at a temperature of about -14°C. Other conditions were as for the pneumatic de-icer. The cylinder was not rotated and the ice grew to a thickness of 3 cm on the front centreline in 20 minutes of icing. As soon as the tunnel was shut down after Run 1, the ice was assailed with a wooden club. The ice was rather mushy, and although it tended to be compressed somewhat by clubbing, it was removed moderately easily. After Run 2, 20 minutes were allowed for the ice to harden before removal was attempted. This time the ice broke off in chunks without much effort; however, no large area of ice was removed in one piece, making removal rather tedious.

Next, the polyethylene foam was covered with the sheet of neoprene rubber, which gave a smoother and more durable surface to the foam. Two more icing runs were made. Thirty minutes were allowed after Run 3 for the ice to harden. The effort required to remove the ice was judged to be about the same as for Run 2. Only five minutes were allowed after Run 4, which was made at a temperature of −8°C, and the ice removal was judged much easier than after Run 1.

In the tests at the outdoor test site it was found that ice could only be removed with some difficulty from polyethylene foam bonded to a flat surface, although with less difficulty than from plain painted steel panels. The compressible foam beneath the ice layer permitted the ice to be cracked and broken with a club or hammer more readily than on an inflexible steel panel; however, the broken pieces of ice generally remained adhered to the rather rough, accommodating surface of the foam, and it was usually necessary, after hammering, to pull the broken pieces off the foam laboriously by hand. In addition, the shattering of the ice frequently cut the foam.

Ice removal from the rubber-surfaced foam was somewhat less difficult and showed a decided temperature dependence. After a run at about −19°C it was noted that the 5 cm thick hard porous ice was moderately difficult to remove using a wooden club, while ice on the steel panels was practically impossible to break and remove by this method. Ice was finally removed by a sledge hammer. Even then, only small amounts of ice could be broken away with each blow. The ice was judged slightly easier to remove at about −16°C, although thin ice (about 1 cm) just splintered, leaving pieces still adhered to the rubber.

At −8°C ice could be removed without too much trouble; after initially breaking it with the club, the ice was lifted off easily by hand. At −3°C the ice was very soft and wet and was easily removed from all panels.

5.1.3 Paint and Varnish

The basic finish on the flat steel panels at the outdoor test site was a black anti-rust paint. During the course of the tests one of the panels was repainted with a grey deck paint, and a wooden panel was finished half in the grey deck paint and half in varnish.

There was no discernible difference in the removal of ice from any of the steel panels, whether painted with the black anti-rust paint or the grey deck paint — they were all equally difficult. Removal became easier as the temperature increased, and little difficulty was experienced at −3°C in removing ice from any of the panels.

The ice was not quite as difficult to remove from the wooden panel, but this was thought to be due to its lower flexural rigidity compared with that of the steel panels. If was judged that the ice released slightly more easily from the grey painted half of the panel than from the varnished half, although the difference was so slight as to be of no real significance.

5.1.4 Freezing Point Depressant

Ethylene glycol was distributed over one area of the vertical steel panel wall of the outdoor test stand. The glycol was fed under gravity from a tank placed 80 cm above a horizontal distribution pipe from which it was discharged through a series of 1 mm diameter holes spaced at 7.6 cm. The discharge holes were so oriented that the glycol flowed onto the panel surface, and as it flowed down the panel surface the individual streams from each hole tended to spread and join, particularly when the surface was wet.

In theory the freezing point depressant should mix completely with the impinging water and form a mixture of which the freezing point is lower than the ambient temperature, thus resulting in complete freedom from icing. In practice it is not possible to ensure ideal distribution, quantity, or mixing of the depressant. Thus ice will form, but this ice is usually infested with the depressant and so is mushy and has poor adhesion to the surface on which it forms; removal is therefore easy.

This was found to be the case. In one run at $-8^{\circ}C$, about a quarter of the panel was free of ice at the end of the test, which deposited about 2.5 cm of ice over the test area. Elsewhere on the panel the ice was just standing clear of the panel and only required a touch to collapse it. In another test at $-10^{\circ}C$ glycol was fed at a rate of 1.1 litre/hr to six panels, i.e. an average rate of 1 litre/hr per 6 m^2. At the end of the run, the glycol-infested ice was broken away from the panels with great ease.

5.1.5 Parallel Filament Rope and Steel Cable

A parallel filament rope was compared with a steel cable. This plastic rope consists of a load-bearing core of highly compressed parallel filaments of polyethylene terephthalate (a linear polyester) covered by a black polyethylene sheath. To quote the manufacturer, "A twistless rope has been evolved which is light, strong, flexible, maintenance-free, and most important — highly resistant to stretch". Most significant from the icing point of view was the smooth polyethylene sheath and its flexibility, which suggested the possibility of low adhesion between ice and rope.

A 6 m length of 2-ton rope (11 mm O.D.) was strung from the top right-hand corner of the mounting frame for the wall panels to the front left corner of the decking (directions as viewed from the front), while for comparison a 6 m length of 12.7 mm, 6 × 19 galvanized steel cable was strung from the top left corner to the front right corner (Fig. 15).

Because of the difference in torsional rigidity between the parallel filament rope and the steel cable, some difference in the manner of icing was observed. The rope, because of its lower torsional stiffness, tended to twist under the weight of ice forming on its windward side, and in so doing more of its circumference would become coated with ice than was the case with the steel cable whose stiffness precluded significant twisting in the short length used. This twisting effect was more marked at lower temperatures or lower water concentrations (Fig. 14) under which conditions more of the impinging water froze on the windward side than at higher temperatures and higher water concentrations, when most of the ice that formed on the cables was in the form of pendant icicles that exerted little torsional moment (Fig. 15).

In extreme cases complete circumferential encapsulation of the plastic rope occurred as a result of the twisting. In one test encapsulation occurred toward the lower end of the rope so that when it was given a good shake by hand only the ice on the upper part of the rope was dislodged. Since the rope and the steel cable contacted at their mid points, shaking the rope also shook the cable, with the result that most of the ice on the cable was also shed. The ice that shed had left the rope completely clean and free of ice remnants, indicating true adhesional release, while small ice remnants still adhered to the steel cable, indicating that the ice had failed cohesively rather than adhesively at the ice/metal interface. In this particular test, ice on the lower part of the steel cable was up to 15 cm thick, with icicles 15 or more cm long.

It was found on this and other occasions that, if ice at the lower end of the parallel filament rope was removed by rapping the iced rope with a club, encapsulating ice further up the rope would slide down and could in turn be broken off. On no occasion was the static weight of the ice sufficient to overcome the adhesive force between the ice and the rope, and so promote a self-protective action.

5.1.6 Discussion and Conclusions

The evaluation of these various methods was very qualitative and the test conditions may not have resembled actual sea icing conditions with any degree of exactness. However, comparative evaluations are thought to be reasonably valid. The use of fresh water instead of salt water is thought to have made the tests somewhat more severe by virtue of the greater strength of fresh water ice. Other mitigating circumstances at sea are the vibration and buffeting experienced in rough weather — conditions that could not be simulated on the simple outdoor test facility.

The pneumatic de-icer proved most effective, both as a mast de-icer and on flat surfaces. There is little doubt that the occasional failure to shed ice on the first inflation of the de-icer would not have occurred under the buffeting of actual sea-going conditions and with a larger active area than used in these tests. Disadvantages of this otherwise most effective method of de-icing are: 1) cost, 2) the likelihood of damage to the de-icers by cutting and abrasion if used in or adjacent to work areas, 3) the danger to hands working on deck from ice falling from above, and 4) the need for removal of the shed ice from the decks if reduction of the total ice weight is to be achieved.

On the other hand, pneumatic de-icing appears to be an ideal method of de-icing the upper parts of masts, etc. to reduce the large heeling moments caused by ice on these parts.

The use of ethylene glycol as a freezing point depressant proved effective in reducing the strength and adhesion of ice on flat surfaces. It is probable that, under the buffeting of sea-going conditions, a fair measure of anti-icing performance would be achieved by this method with the flow rates used in these tests. This method of icing prevention may prove useful for small components such as radomes and inflatable life raft containers. Its disadvantages when used in work areas are: 1) a slippery residue could be left on the decks after an icing encounter if not completely flushed away by water, and 2) a danger exists of contamination of the fish catch.

The various coatings and finishes tested were not considered very successful. The most successful was the rubber-covered plastic foam. This was because the deformable foam substrate permitted breaking of the ice with moderate ease, while the ice exhibited lower adhesion to the smooth rubber surface than to the pebbled surface of the bare polyethylene foam. The rubber also provided a durable surface to the otherwise easily damaged foam. No case occurred of ice falling off the foam or rubber-covered foam under its own weight, as suggested by the Japanese work; this may be due partly to the small panel size, partly because of the lack of vibration and buffeting, and also perhaps because most of the tests were made at temperatures well below the freezing point with fresh water instead of sea water.

In addition, although on the Japanese vessels of steel construction the mats were cemented on, in the case of the vessels of wooden construction the mats were affixed with steel straps at the top, bottom, and sides of each mat, and the resulting diaphragm action of these mats under the action of the sea undoubtedly was the reason that "there was little icing on the mats, and ice was sprung off every time there was any kind of shock or shaking".

A disadvantage of this method is the problem, also encountered in the Japanese tests, of effectively bonding or attaching the foam and rubber blankets to flat surfaces. However, little difficulty is seen in lacing blankets on masts, etc., much in the manner used for the pneumatic de-icer. This might prove useful in work areas where the use of pneumatic de-icers may be prohibited because of the damage hazards.

If the various methods are rated in order of de-icing effectiveness or ease of ice removal, the following list results:

1. Pneumatic de-icer
2. Freezing point depressant
3. Rubber-surfaces plastic foam on steel panel
4. Paint or varnish on wooden panel
5. Bare polyethylene foam on steel panel
6. Paint on steel panel.

In spite of the obviously lower adhesive strength of ice to the polyethylene sheath of the parallel filament rope than to the zinc galvanizing of the steel cable, little difference was observed in the ease of removal of ice, even though it released cleanly from the rope, while cohesive failure of the ice resulted in residual ice fragments remaining on the steel cable. During these tests, encapsulation occurred on the plastic rope only, because of its lower torsional rigidity; however, in stays that are more vertical, twisting would be less likely, but ice encapsulation might be more likely to occur as a result of the flow of water around the cable. Under these circumstances difficulty would certainly be encountered in removing ice from steel cables; however, the tendency for ice to slide down the rope once ice at a lower level had been removed would permit the removal of ice from otherwise out-of-reach locations. A major disadvantage of the parallel filament rope is the ease with which it can be cut, thus limiting the locations at which it could be employed aboard ship.

6.0 LOCAL CONDITIONS OFF EASTERN CANADA

The sea area of interest in this study lies approximately between the latitudes 42°N and 60°N and between the 45°W meridian and coast of North America. In this area the combination of strong winds and low air temperatures, two of the factors required for icing, are provided by the passage of intense cyclones. Archibald (Ref. 36) states that, for a five-year period (1963-67) for January, February and March, the predominant path of the most intense storms lies right along the Nova Scotia coast and across the southern part of Newfoundland, with a somewhat less frequent track lying parallel and south-eastward of this predominant track. This is illustrated in Figure 16 which is reproduced from Archibald's paper. The dots with concentric circles around them indicate the position of maximum intensity of the centre of the most intense storms, i.e. those with a pressure at the centre of between 956 and 972 mb and with a very steep pressure gradient. Less intense storms, with pressures of between 972 and 980 mb, are represented by solid dots. It is clear that many of these storm centres will produce in their wake strong northerly or northwesterly winds carrying cold Arctic air to the sea area of interest. The result is, therefore, that these regions are particularly susceptible to the meteorological conditions most conducive to icing.

The oceanographic conditions of interest are the sea-surface temperature, the sea state and, to a lesser extent, the sea-surface salinity.

Monthly mean sea surface temperatures are presented in Reference 37. Those for February, which do not differ very significantly from those for January and March, are shown in Figure 17. These show cold water, with temperatures down to about -1°C adjacent to land or to the sea ice cover, slowly increasing in temperature with distance from land such that the 8°C isotherm lies about 150 nautical miles off the southern tip of Nova Scotia (Cape Sable), some 250 nautical miles off Cape Race, Newfoundland, and considerably more removed to the east of Newfoundland and Labrador.

The roughness of the sea depends not only on the wind strength, but also on the fetch and the duration of the wind (Ref. 38). This is illustrated in Table I. Some sheltering of the fishing grounds off Nova Scotia and south of Newfoundland from northerly winds is afforded by the proximity of the land; a large part of the winter fishing is done within 100 nautical miles of land, resulting in significant reduction in potential wave height for winds of Force 6 and above. However, a large part of the St. Pierre Bank (45° — 47°N, 55° — 57°W) and the Scatari Bank (46°N, 59°W) is not protected from the north-westerly winds which sweep across the Gulf of St. Lawrence and through the Cabot Strait. Similarly the fetch may be considered unlimited over most of the Grand Banks and for sea areas east of Newfoundland.

The freezing temperature of sea water is a function of its salinity and may be represented by the expression:

$$t = -0.002 - 0.0524S - 0.00006S^2$$

where S = salinity in parts per thousand (‰),
and t = equilibrium freezing temperature (°C).

This expression is within 0.002°C of the tabulated values of the freezing (melting) temperature of sea water as quoted by List (Ref. 39) for salinities from 0 to 40‰.

The mean isohalines (Ref. 37) for the three winter months January to March indicate a considerable variation in the area of interest, from about 30‰ (parts per thousand) in the Cabot Strait to about 35‰ at the southern edge of the Grand Banks. However, this variation in salinity only results in a variation in the freezing temperature of about a quarter of a degree, i.e. from about -1.65°C to -1.9°C, as Figure 18 demonstrates, hardly significant enough to have any effect on the onset or the severity of icing.

These considerations lead to the conclusion that conditions conducive to frequent and severe icing occur in the area under consideration during the winter months.

To investigate these conditions further, to compile statistics on the frequency and severity of icing encounters, and to determine actual geographical extents of icing condictions, data have been collected by means of voluntary reports using a standard report form. The next section will discuss this programme.

7.0 ICING REPORTING PROGRAMME

Icing report forms were distributed jointly by the Ship Safety Branch of the Canadian Coast Guard and the Division of Mechanical Engineering of the National Research Council of Canada to all vessels, but primarily fishing vessels, operating out of Canadian east coast ports. Forms were distributed to some 350 fishing and other vessels over 20m in length. Of these, about 240 are 30m or longer, and it is estimated about 70% may be at sea at any one time. Reporting was voluntary, and as a result rather variable, both as regards compliance and the quality of the response; however, in general, both the quantity and the quality of the responses improved with time. Reports were received from only about 15% to 20% of the vessels over 30m length, while on any one day no more than about 10% of the vessels actually at sea made out reports, even when icing conditions were severe.

The report forms themselves underwent several modifications during the survey period in an attempt to make them simpler and more acceptable to the user, while at the same time providing as much relevant data as possible. The current version of the form is shown in Figure 19. Earlier versions were presented in Refs. 15 and 40.

Ships' masters were urged to make returns even when no icing was encountered on a trip (i.e. a null report) so that a better appreciation of the frequency of icing encounters could be gained. In general only a handful of masters were assiduous in this, so that frequencies of occurrences are based only on a proportion of the vessels responding, the number of which varied from year to year, as did the area in which the vessels operated.

Table II shows the number of vessels responding each year as well as the number of reports submitted.

7.1 Severity Statistics

Based on the reports from all vessels for seven winters and on the reported severity of icing (i.e. the subjective assessment given by the ship's officer making the report), statistics on the daily expectation of various degrees of assessed severity for each of the winter months have been compiled. The results are presented in Table III. For each of the months, December to March, and for the complete 4-month period, 1 December to 31 March, the Table gives the number of days that icing of severity light or greater, moderate or greater, or heavy was reported. The yearly average number of days and standard deviation from this average is shown. The great variability from year to year for the months of December and March is evident by the high standard deviations (approximately 90% of the averages). Much greater yearly consistency is evident for the months of January and February. Based on on these 7 years (1970-71, 1971-72, 1973-74, 1975-76, 1976-77, 1977-78, and 1978-79) the daily expectation of experiencing icing of the three severity categories is given; for example, in December more than trace icing may be expected on about 15% of the days (i.e. about 5 days) while in February this expectation is some 50% (14 days). Similarly, for the 4 month season, the daily expectation is 36% (43 days) for light icing or greater, while heavy icing may be expected on 11 days (9%).

It should be noted that the data of Table III relate to icing reported from throughout the study area. Because vessels are not necessarily in every part of the study area at all times, these statistics may in some cases rather underestimate the frequency of occurrence.

Frequencies in specific areas within the total study areas may be expected to be lower than the overall frequencies given in Table III. Two specific areas have been selected for similar analysis, namely Divisions 3L and 3P of the area designated by the International Commission for the Northwest Atlantic Fisheries (ICNAF), and shown in Figure 22. Table IV presents the results for the ICNAF Division 3L and suggests frequencies of about one third of those for the total study area, with frequencies of about 15% (4 to 5 days per month) for icing of at least light severity during the months of January and February. In February the frequency drops to 5.6% for moderate or greater severity with large yearly variability, the likely cause of this being the encroachment of sea ice into this area to a greater extent some years than others. The results for the ICNAF Division 3P (the Sub-divisions 3Pn and 3Ps are combined) are given in Table V. In this sea area the frequencies of occurrence are seen to be generally slightly over one half of those for the total study area, except for the month of December when frequencies of less than 2% are experienced. The higher frequencies for December seen in Table III for the total area result largely from icing reports from more northerly sea areas.

The foregoing statistics relate to the subjective icing severity assessments as made by the ships' officers, and there is little reason to question these assessments in view of the great experience these men have of icing conditions each winter and of the ice handling qualities of their respective vessels. However, these statistics relate more to the rate of icing experienced rather than to the total ice accumulated on the vessels. Since the amount of accumulated ice is the significant factor as far as the stability and handling qualities of the vessel are concerned, and is of special significance to regulating bodies concerned with the safety of ships at sea, statistics based on ice accumulation have been compiled.

Since most nations with significant deep sea fishing fleets subscribe to the recommendations on the stability of fishing vessels of the Inter-Governmental Maritime Consultative Organization (IMCO), it has been found convenient to express the degree of icing in terms of the IMCO icing allowance criterion.*

Based on seven years of data using returns from only those vessels for which a relatively complete history of voyages throughout the winter season was available, Table VI has been drawn up and updates that presented in Reference 42. The degree of icing is based on the thicknesses of ice on various parts of the vessel as reported in the questionnaire (Fig. 19), and converted rather arbitrarily to multiples or sub-multiples of the IMCO criterion using the points system illustrated in Figure 20. The application of this points system is most easily demonstrated by the use of an example. In this example it will be assumed that the following ice thicknesses have been reported:

a) Diameter of ice on forward rails	75-100 mm (3-5 in.)
b) Diameter of ice on other rails	75-100 mm (3-5 in.)

---

* The Recommendation on Intact Stability of Fishing Vessels (Ref. 41) of the Inter-Governmental Maritime Consultative Organization (IMCO) lays down the following minimum ice allowance in calculating a vessel's stability.

a) 30 kg/m^2 on exposed weather decks and gangways,

b) 7.5 kg/m^2 for the projected lateral area of each side of the vessel above the water plane.

Criterion a) above implies an average ice thickness of about 35 mm or 1½ in. while b) corresponds to an average thickness of roughly 9 mm or 3/8 in.

c)	Diameter of ice on forward stay	> 100 mm (> 5 in.)
d)	Thickness on main deck	50-75 mm (2-3 in.)
e)	Thickness on boat deck	25-50 mm (1-2 in.)
f)	Thickness on wheelhouse font	50-75 mm (2-3 in.)
g)	Thickness on bulwarks	25-50 mm (1-2 in.)

Thus, using Figure 20, (a) is rated 4 points, (b) 8 points, (c) 8 points, (d) 8 points, (e) 4 points, (f) 8 points and (g) 4 points. The points total is therefore 44, which falls in the range 36-48, thus indicating a rating equivalent to 1½ times the IMCO icing allowance.

Table VI shows the percentage of voyages on which icing of the indicated degree was encountered by the assemblage of vessels. If icing was encountered more than once on a voyage, only the more severe encounter was used in these statictics. The period covered is a typical icing season, from roughly the middle of December to the end of March (approximately 100 days). During this time an individual vessel makes some 7 or 8 trips having a typical duration of about 10 to 12 days.

The totals for the seven years for which statistics could be obtained show there is a 40% probability of icing of some degree being encountered on a voyage to the fishing grounds during the icing season. It is also shown that on 8% of winter voyages the degree of icing encountered will exceed the IMCO icing allowance, while 2.5% of voyages will experience icing of greater than twice the IMCO standard.

7.2 Geographical Distribution of Icing

The locations of icing encounters given by some 450 ship icing reports are shown in Figure 21. They indicate that icing may be encountered anywhere within the continental shelf zone of Eastern Canada as well as the adjacent deeper waters of the Labrador Sea. The very large sea temperature gradients existing off the Scotian Shelf and the Newfoundland Grand Banks as a result of the warm Gulf Stream provide a very definite limit to the southern extent of icing (Ref. 5).

For more detailed study, the sea areas in which icing occurrences have been reported are conveniently defined in terms of the Divisions designated by the International Commission for the Northwest Atlantic Fisheries (ICNAF). Figure 22 is a map showing these Divisions. In reporting the areas of icing occurrences it is found convenient to combine Divisions 3Pn and 3Ps into a single Division 3P, and to redefine the boundary between Divisions 4Vn and 4Vs by moving it south to the parallel 44°10′N, such that the bulk of the continental shelf within 4V is in the redefined Division 4Vn.

The reports suggest that there are preferred fishing areas, which nevertheless tend to vary somewhat from year to year and even from month to month, partly as a result of the availability of fish stocks and also as a result of the encroachment of sea ice, both southward along the coasts of Labrador and Newfoundland and within the Gulf of St. Lawrence. Thus it is not possible to interpret the total number of icing reports from various areas as indicating the relative frequency and/or severity of icing in the respective areas at any given time. However, by taking reports of icing in individual ICNAF Divisions for each of the winter months over a number of years it becomes possible to determine whether there is a likelihood of experiencing icing in a given Division and month. Eight years of data have been analyzed by Division and month to determine whether any cases of icing of severity greater than slight (i.e. half IMCO criterion or greater) have been reported. The results are presented in Table VII and illustrated as percentages for each month in Figures 23 to 28.

Since a required condition for serious icing according to various sources (Refs. 3, 4, 7, 8) is a combination of air temperature below the freezing point of sea water (about −1.8°C) and sea-surface temperature below about +5°C, it is to be expected that such a combination could also be used to define areas of expected icing. Thus in Figures 29 to 34 isotherms of 40°F (4.4°C) mean monthly sea-surface temperature as given in Reference 37, and isopleths of 10% percentage frequency of air temperatures of 0°C or less as given in Reference 43 are shown. The actual isotherms of both sea and air will vary throughout each month and their monthly means will vary from year to year; however, comparing Figures 23 to 28 with Figures 29 to 34 does suggest that these monthly means taken in combination do predict the areas where icing is to be expected during the month.

In November (Figs. 23 & 29) no icing has been reported south of 48°N, and all instances have been close to the Labrador or Newfoundland coasts, observations which accord with the sea and air temperature criteria. That icing has not been reported more northerly than about 57°N during November is doubtless due to the sparseness of Canadian fishing activity in these waters; nevertheless the potential for serious icing in the Davis Strait area exists. Later in the winter the southerly advance of sea ice tends to set a northern limit to significant icing since the ice cover inhibits wave action and hence spray. Light to moderate icing, however, may still be experienced wherever sufficient open water is encountered. Considerable variability in ice coverage from year to year occurs.

In December (Figs. 24 & 30) the possibility of encountering icing moves further south with the advance of the cold water and the lowering air temperatures. Probabilities are still low in most areas, and no encounters have been reported in ICNAF Divisions 3M, 3N and 4Vs. The single report of icing in Division 3-0 was on the boundary with 3L and 3P, so that the 13% probability indicated may be misleadingly high.

January (Figs. 25 & 31) shows considerable increase in icing probabilities, with the cold water now covering all of the Canadian continental shelf. The pattern for February (Figs. 26 & 32) differs little from that of January except for the advance of sea ice off the Labrador/Newfoundland coast and in the Gulf of St. Lawrence.

March (Figs. 27 & 33) sees a general lessening of icing probabilities as the air temperature begins to moderate, while only isolated cases of icing have been reported in April (Figs. 28 & 34).

7.3 Meteorological Conditions Causing Icing

For the most part the icing reports revealed that icing occurrences followed closely upon the passage of well-developed low pressure systems through the area (Ref. 5). These systems bring in their wake cold Arctic air down over the fishing grounds and the reports indicate that they influence the area for only a matter of a day or two at a time. Figures 35 and 36 illustrate such systems. Occasionally, however, an extensive outbreak of cold air will establish itself over the eastern part of the continent for a more extended period, and then icing conditions may persist for a week or two but with occasional lulls. Systems responsible for a few of the more severe icing conditions in recent years are illustrated in Figures 37 to 40.

One extended period of icing was from 26 January 1972 to 10 February 1972, and Figure 37 shows the weather pattern prevailing at 1200 G.M.T. on 27 January 1972. Some icing was reported each day throughout this period with severe icing being experienced on 26 to 28 January, 2 February, 6 February and 9 February, so that many vessels took precautionary action such as dodging into wind or sheltering in the lee of land. During these severe periods air temperatures as low as −18°C and winds of up to force 11 (60 knots) were reported, while the sea temperature where many of the reporting vessels were operating was in the range 0 to 3°C. Such conditions can result in very severe icing, and indeed this is borne out by many of the reports, since icing rates in excess of 15 cm/24 hr were evidenced on several occasions. One stern trawler of 630 gross tons reported an estimated accumulation of 200 tons of ice — this was clearly a gross overestimate, but ice thicknesses of up to 20 inches (51 cm) occurred despite several de-icings over a period of 40 hours; the stability of the vessel was reported to have been noticeably affected. Another stern trawler of 620 gross tons landed at Halifax in an iced-up condition; ice from several locations was removed and weighed, and based on these weights and the thickness of ice at various positions a total ice weight of 30.81 tons was arrived at, having a vertical centre of gravity of 9.32 feet (2.84 m) above deck at midships. The ice allowance for this vessel in its stability calculations is 30 tons with a centroid 9.95 feet (3.03 m) above the level of the deck amidships. The greatest ice thickness on this vessel was 12 inches on the forward house front (Fig. 41). A government survey ship of 65 m overall length sailing from Newfoundland to Halifax in the same period picked up an estimated 150 tons of ice and reported an increased roll period; Figure 42 shows some of this ice build-up in the forecastle area.

These occurrences suggest that, compared with the IMCO recommendations, the more severe ice allowance imposed by Canada (Ref. 44) on vessels sailing in northern or eastern Canadian waters is not unrealistic for these areas.

Another extended period of icing was the 12 days from 9 February 1979 to 20 February 1979, with particularly severe conditions prevailing on 14 and 15 February. The synoptic situation at 0000 G.M.T. on 14 February is shown in Figure 39 while that at 1800 G.M.T. on 15 February is shown in Figure 40. The more southerly low, centred at about 40°N 55°W at 0000 G.M.T. on the 14th, deepened and moved around the area of low pressure centred just off the Labrador coast. By 1800 G.M.T. on the 15th, the latter had dissipated off the northerly tip of Newfoundland while the former had reached its greatest intensity and was centred just south of Greenland. Throughout this period, cold air streamed across Labrador and the sea areas off Newfoundland and Nova Scotia.

7.4 Relation Between Reported Severity and Temperature and Wind Conditions

To demonstrate the effect of air temperature and the relative wind speed on the reported icing severity, Figures 43 and 44 have been constructed using two winters' reports (1971-72 and 1975-76), for vessels steaming at 5 knots or greater (Fig. 43) and for vessels making less than 5 knots (Fig. 44), i.e. when riding out the storm (dodging) or when fishing. Although best fit hyperbolae have been drawn for each severity level, considerable scatter of the data points exists and no clear-cut transition from one severity to another emerges; nevertheless the trend is apparent. The scatter may be attributed to the various factors enumerated in Section 2 above as well as to the subjective nature of the reported icing severities.

Figures 43 and 44 may therefore be regarded as no more than rough rules of thumb in predicting icing severity if only the air temperature and wind velocity are known. Figure 43 suggests that when steaming, heavy icing may be expected if the product of the relative wind speed (in knots) and the air temperature (in °C below 0°C) is greater than about 400, while when dodging or fishing (Fig. 44) the criterion for heavy icing increases to a product in excess of about 500. Both figures suggest that with products of relative wind speed and air temperature less than 200, the icing severity is of little or no significance.

In the following section, an attempt is made to quantitatively predict the rate of ice build-up on a vessel using an analytical approach.

8.0 PREDICTION OF RATE OF ICING

Certain empirical approaches have been devised to determine more or less quantitatively the severity of icing from the prevailing sea and atmospheric conditions; perhaps the best known of these is due to Mertins (Ref. 45). In his approach, Mertins, in addition to air temperature and wind force, introduced the effect of sea-water temperature and presented his results in the form of four charts (Fig. 45).

More recently, Comiskey (Ref. 46) has taken Mertins' four charts and made them more convenient to use by combining them into one chart, as shown in Figure 46.*

A quantitative rate of icing may be approximated from both the Mertins and Comiskey charts by interpolation using the range of icing rates given for each icing category.

Applying some of the data reported by means of our icing questionnaires, the Mertins/Comiskey charts give good correlation in those cases when the vessels are steaming (between about 5 knots and 12 knots) but tend to underestimate the icing rates derived from the reports by a factor of about 0.7. In cases when the vessels are at low speed (dodging or fishing) correlation is not so good and generally the charts rather seriously overestimate the icing rate. Wind speeds relative to the vessels were used rather than absolute wind speeds, as these gave somewhat improved results.

---

* Since writing this, modifications to the Comiskey chart have been made. See the NOAA report by Wise and Comiskey in the Bibliography of Appendix C.

Kachurin et al (Ref. 47) have taken an analytical approach and calculate the rate of icing of a cylindrical rod under conditions similar to the spray icing of small fishing boats, and relate this to the ice build-up rate observed on actual ships. This approach appears to be useful, but as formulated by Kachurin tends to be rather complex inasmuch as he introduces time dependent effects.

Such sophistication seems to be rather unjustified in view of the many uncertainties in meas-uting or estimating the various atmospheric and ocean parameters as well as a representative rate of icing for the vessel. Therefore in Reference 42 an expression was developed for estimating the rate of icing on a ship, wherein only the primary heat transfer terms were considered, and where in addition the ice formation process was considered to be a continuous, quasi-steady state process, notwithstanding that the water arrives at the icing surfaces in a rather discontinuous manner.

In Appendix B of this report an amended version of the analysis given in Reference 42 is presented wherein the drop cooling equation is modified to include the effect of evaporative cooling, as well as certain other minor modifications.

The final expression for the rate of icing, N_i*, derived in Appendix B is:

$$N_i* = 0.00425\, H_w V_{kt} (t_s - t_d) + 0.0369\, V_{kt}^{0.8} \left\{(t_s - t_a) + 17.3\,(e_s - 0.9\, e_a)\right\} \text{mm/h}$$

where H_w = wave height, m

V_{kt} = relative wind speed, kt

t_s = equilibrium temperature of the icing surface, °C

t_d = temperature of impinging water drops, °C

t_a = air temperature, °C

e_a, e_s = saturation vapour pressure of moist air at temperature t_a, t_s respectively, kPa

In order to test this model of icing under conditions of sea spray, the icing rates as calculated by this equation using the conditions applicable to 39 reported icing indicents have been compared with the mean icing rates derived from these reports. This comparison is shown in Figure 47; however, before discussing this comparison, some discussion of the data on which it is based is necessary.

8.1 Discussion of Observed Data

The relevant observed and derived data for 39 reported icing incidents in the two seasons 1977-78 and 1978-79 are presented as Table VIII. Only data from fishing trawlers are used; those from freighters, tankers and government vessels of various types have not been included because of the different size and lines of these vessels, and until some means of incorporating these two variables into the analysis is developed, each class of vessel must be treated separately. Even among the fishing trawlers considerable size and design variation exists which undoubtedly results in part in some of the scatter of the data.

Scatter may also be caused by numerous undertainties in the data, as the following discussion indicates.

The reported wind speed and direction are combined with the vessel speed and heading to derive the wind speed and direction relative to the ship. The relative wind speed is entered as column 3 of Table VIII. Data sets (entries) Nos. 1 to 32 are for relative wind directions of 0 ± 45°, while entries 33 to 39 are for those cases of beam or quartering winds (i.e. $0 > \pm 45°$). Some uncertainty exists in interpreting the reported data since in many cases the reported wind velocity may in fact be the relative velocity rather than the true velocity, and it is not always made clear whether the ship heading is magnetic or true.

The air temperature may be expected to be fairly reliable, assuming that the thermometer used is in calibration and that the thermometer bulb is not exposed to the water spray. Some vessels are evidently not equipped with thermometers, and so data from them could not be used except where temperatures could be inferred from other vessels operating in the same area at the same time.

The sea water temperature entered in column 5 of Table VIII is derived, knowing the vessel location, from weekly sea-surface temperature charts compiled by the Canadian Forces Meteorology/ Oceanography Centre, Halifax.

The wave height is not always quantitatively reported and in most instances has been inferred from a qualitative description of the sea state using the following scale derived from the State of Sea table in the Trawlermen's Handbook (Ref. 48).

Description	Inferred Wave Height — m
slight	0.6 - 1.2
moderate	1.2 - 2.5
rough	2.5 - 4
very rough	4 - 6
high	6 - 9
very high	9 - 14

If, as stated in Appendix B, the liquid water content of the spray is primarily a function of wave height, then this is an important parameter in the analysis, but one which is subject to considerable uncertainty because of the necessity of interpreting the qualitative descriptions given in the reports. Relationships relating wave height to wind speed exist, but these usually apply to winds of unlimited duration and fetch, conditions which do not apply to the majority of the fishing trawler icing events because of their proximity to land or to an ice cover.

The salinity of the sea water in the location of an icing report has been derived from the Mean Sea Surface Salinity charts given in the Oceanographic Atlas (Ref. 37). Because changes in salinity within the range to be expected in this area (i.e. $30‰ < s < 35‰$) do not greatly affect the icing rate, secular variations from the salinity values given in the charts are of little significance.

Perhaps the greatest uncertainty arises in the derivation of icing rate (column 8). A mean or representative ice thickness was assessed from the thicknesses reported for the various on-board locations indicated in the Icing Report (Fig. 19). In assessing the mean thickness, somewhat less weight was accorded the ice thickness on the forward rails and stay, since these thicknesses were not necessarily representative of the vessel as a whole. The reporting of duration of icing occasionally left some uncertainty, particularly when icing was intermittent, in which case what should have been reported as separate events were sometimes reported as one extended event. Sometimes, too, it was not made clear whether some de-icing action that could have affected the reported ice thicknesses, had been taken during the icing encounter.

Other undertainties arise because of changing conditions during the encounter. Often such changes (in wind, temperature, etc.) are not indicated. Clearly, the longer the reported encounter, the more uncertainties there are, so that no encounter of duration greater than 24 hours has been used in Table VIII.

8.2 Discussion of Icing Rate Results

Employing Equation (B.31c) of Appendix B and the iterative techniques described (Section B.1.7), the data of columns 2 to 7 of Table VIII were used to obtain calculated rates of icing (column 9 of Table VIII). These are compared in Figure 47 with the rates of icing as derived from the icing reports (column 8 of Table VIII). Also shown in the figure is the line passing through the origin that gives the best least squares fit between the two sets of values. The correlation coefficient is r = 0.55.

That there is so much scatter in Figure 47 is perhaps not unexpected in view of the numerous uncertainties in the raw data discussed in sub-section 8.1. It is encouraging in fact that the calculated rate is generally within an order of magnitude of the assessed rate, which gives a certain degree of confidence in the calculations; however, a more complete test of the theory cannot be made until more consistent and reliable data is available. That some of the present data is "bad" may be seen by comparing some of the entries in Table VIII, c.f. entries 1 and 15, 25 and 33, 7 and 15, 10 and 21, etc. where lower reported icing rates correspond to clearly more severe conditions.

Figure 47 does not suggest that a beam wind results in a significantly different rate of icing than a bow wind, nor can any consistent effect of vessel length be observed.

The rate of icing Equation (B.31c) may be used to show the relative effects of the various parameters contributing to the heat balance. This is illustrated in Figure 48 where one parameter of a set of standard conditions has been varied in turn throughout its likely range. The standard conditions chosen were:

Air temperature	T_a	=	$-10^\circ C$
Sea-surface temperature	T_w	=	$0^\circ C$
Relative wind speed	V	=	40 kt
Wave height	H_w	=	3 m
Salinity	S	=	32‰
Relative humidity	RH	=	90%

Figure 48 indicates that the most significant variables in determining the icing severity are the air temperature and the relative wind speed. The sea-surface temperature, the wave height and relative humidity are seen to be of more moderate significance, while the salinity of the sea water is shown to have the least effect on rate of icing of these six variables.

The results demonstrated in Figure 48 therefore suggest that, in view of the quality of the available data, a simplification may be made to the Rate of Icing equation by assuming a constant salinity and a constant wave height (i.e. a constant water content, say 0.0005 kg/m^3). Further simplification may be made by assuming that the icing surface temperature is identical to the freezing temperature of the sea water. If then the icing surface temperature is taken as $-1.8^\circ C$, there results the simplified equation:

$$Ni^* = 0.013\,(-t_d - 1.8)V + 0.0369V^{0.8}\left\{(-t_a - 1.8) + 17.3\,(0.5354 - 0.9\,e_a)\right\}$$

in which only T_d has to be determined from Equation (B.14) and e_a by Equation (B.28).

The application of this equation to the data of Table VIII results in a plot not significantly different from Figure 47 (i.e. a correlation coefficient of 0.57 and the best fit line through the origin having a slope of 0.74).

9.0 CLOSURE

This report has collated and reviewed the work in the programme on the icing of fishing trawlers that the Low Temperature Laboratory has done over the eleven-year period 1969 to 1979. Because of budgetary restraints this work has been very low key in nature.

Initially, some simple icing tests (Ref. 17) on cylinders of various diameters were made in the icing wind tunnel to demonstrate the effects of air temperature and cylinder size on the resulting ice formations. The main conclusion from these tests was that the icing efficiency of a cylinder increases both with decreasing diameter and with decreasing temperature, a result that demonstrates the need to reduce small scale components such as spars, rigging, etc. to a minimum, and where they cannot be eliminated altogether, wherever possible to let one larger diameter component serve the purpose of several smaller ones.

Among a number of simple methods tested as possible means of reducing the icing hazard (Ref. 27), no passive method was found to significantly ease the removal of ice from a surface. However, an inflatable rubber de-icing blanket was found to be remarkably effective in removing ice from both cylindrical and flat surfaces.

Icing report forms have been distributed since 1969 to vessels operating out of eastern Canadian ports. The data obtained by this means has helped to establish the type of weather systems responsible for icing conditions, the geographical extent of the occurrence of icing, and statistics on the severity of icing encounters in the study area.

The geographical extent varies from month to month, but at its most extensive covers the whole of the continental shelf off Eastern Canada as well as the Labrador Sea. The type of weather system mostly responsible for severe icing in these areas is a well-developed low pressure system, in the wake of which cold Arctic air is brought down over the fishing grounds by vigorous northerly or northwesterly winds.

The reports show that during January and February icing conditions of light or greater intensity occur on the average one day out of two somewhere in the study area, while in bad years this may increase to nearly three days in four. In terms of the amount of ice accumulated, it is shown that on approximately 8 percent of voyages during the winter season, ice accumulations in excess of the allowance recommended by IMCO in calculating the vessel's stability were experienced.

Finally, an analytical approach to the prediction of the rate of ice build-up on a fishing trawler is presented. This analysis (with possible minor modifications) has application also to the icing of marine structures.

10.0 REFERENCES

1. Hay, R.F.M. — *Ice Accumulation upon Trawlers in Northern Waters.* Meteorological Magazine, London, Vol. 85, 1956, pp. 225-229.

2. Tabata, T., Iwata, S., Ono, N. — *Studies of Ice Accumulation on Ships. Part I.* National Research Council of Canada, Technical Translation, TT-1318, 1968. Also published as Defence Research Board, Canada, Translation T93J, 1967.

3. Borisenkov, E.P., Panov, V.V. — *Basic Results and Prospects of Research on Hydro-meteorological Conditions of Shipboard Icing.* In: Investigation of the Physical Nature of Ship Icing by E.P. Borisenkov et al, U.S. Army, Cold Regions Research and Engineering Laboratory, Draft Translation 411, 1974, pp. 1-30.

4. Dacam, D.J. — *Ice Accretion on Ships.* In: Seminar on Trawler Safety, Naval Scientific and Technical Information Centre, U.K., NSTIC/28990, 1970, pp. 3-8.

5. Stallabrass, J.R. — Meteorological and Oceanographic *Aspects of Trawler Icing off the Canadian East Coast.* The Marine Observer, London, Vol. 41, 1971, pp. 107-121.

6. Small, T.V. — *Icing at Sea.*
Journal of the Royal Naval Scientific Service, Vol. 26, 1971, pp. 364-371.

7. Vasil'yeva, G.V. — *Hydrometeorological Conditions Causing Ice Accretion on Ships.*
Defence Research Board, Canada, Translation T486R, 1967.

8. Shekhtman, A.N. — *Hydrometeorological Conditions in the Icing-up of Vessels at Sea.*
Naval Scientific and Technical Information Centre, U.K., Translation No. 2311, 1971.

9. Langham, E.J., Mason, B.J. — *The Heterogeneous and Homogeneous Nucleation of Supercooled Water.*
Proceedings Royal Society, A., Vol. 247, 1958, p. 493.

10. Fletcher, N.H. — *The Physics of Rainclouds.*
Cambridge University Press, 1962, p. 220.

11. —— — *Trawler Icing Research.*
BSRA Report 221, British Shipbuilding Research Association, London, 1957.

12. Albrecht, F. — *Theoretische Untersuchungen über die Ablagerung von Staub Strömender Luft und 1 hre Anwendung auf die Theorie der Staubfilter.*
Phys. Zeitschr. Vol. 32, 1931, pp. 48-56.

13. Taylor, G.I. — *Notes on Possible Equipment and Technique for Experiments on Icing of Aircraft.*
Ministry of Aircraft Production, Aeronautical Research Committee, R.& M. No. 2024, January 1940.

14. Langmuir, I., Blodgett, K.B. — *Mathematical Investigation of Water Droplet Trajectores. July 1945.*
In: Collected Works of Irving Langmuir, Vol. 10, Gen. Ed: C.G. Suits, Pergamon Press, N.Y., 1960, pp. 348-393.

15. Stallabrass, J.R. — *Icing of Fishing Vessels in Canadian Waters.*
National Research Council Canada, DME/NAE Quarterly Bulletin No. 1975(1), April 1975, pp. 25-43.

16. Messinger, B.L. — *Equilibrium Temperature of an Unheated Icing Surface as a Function of Air Speed.*
Journal of Aeronautical Sciences, Vol. 20, No. 1, 1953, pp. 29-42.

17. Stallabrass, J.R., Hearty, P.F. — *The Icing of Cylinders in Conditions of Simulated Freezing Sea Spray.*
National Research Council Canada, Report MD-50, 1967.

18. Dickey, T.A. — *Variables Determining the Form of an Ice Accretion.*
U.S. Navy Naval Air Material Center, Report No. AEL-1206, 1952.

19. Lozowski, E.P., Stallabrass, J.R., Hearty, P.F. — *The Icing of an Unheated Non-Rotating Cylinder in Water Droplet-Ice Crystal Clouds.*
National Research Council Canada, Report No. LTR-LT-96, 1979.

20. Lee, A. — *Ice Accumulation on Trawlers in the Barents Sea.*
Marine Observer, Vol. 28, No. 181, 1958, pp. 138-142.

21. Holland-Martin, Sir. D. — *Trawler Safety.*
Final Report of the Committee of Inquiry into Trawler Safety.
H.M.S.O., para. 138, July 1969, p. 57.

22. Tabata, T. — *Research on Prevention of Ship Icing.*
Research Board (Canada), Translation No. T95J, July 1968.

23. Sewell, J.H. — *The Design and Development of New Ice-Shedding Coatings.*
U.S. Army Aviation Systems Command, USAAEFA Project No. 74-77, Rotary Wing Icing Symposium, Summary Report Vol. II, June 1974, pp. 37-50.

24. — — *De-icing Apparatus for Ships.*
Polar Record, Vol. 15, No. 96, 1970, pp. 343-4.

25. — — *Electro-Impulse De-icing System.*
Tech Air, Vol. 27, No. 9, 1971, pp. 6-9.

26. — — *Electro-Thermal Heating System for Protection of Aircraft and Ships Against Icing.*
Polar Record, Vol. 10, No. 64, 1960, pp. 68-70.

27. Stallabrass, J.R. — *Methods for the Alleviation of Ship Icing.*
National Research Council of Canada, Report MD-51, 1970.

28. Ford, T.F.; Nichols, O.D. — *Adhesion-Shear Strength of Ice Frozen to Clean and Lubricated Surfaces.*
U.S. Naval Research Laboratory, Report 5832, August 1962.

29. Landy, M.; Freiberger, A. — *An Approach to the Shipboard Icing Problem.*
Naval Engineers Journal, Vol. 80, No. 1, 1968, pp. 63-72.

30. Ackley, S.F.; Itagaki, K. — *Ice Adhesion Studies: Properties of Defects in the Interface Region.*
U.S. Highway Research Board, Special Report 115, "Snow Removal and Ice Control Research", 1970, pp. 87-96.

31. King, R.D. — *Hyviz — A New High Light Transmission and Electrically Conducting Film for Heating of Ships' Bridge Windows.*
Marine Engineers Review, May 1973, pp. 37-38.

32. Lock, G.S.H. — *Some Aspects of Ice Formation with Special Reference to the Marine Environment.*
Paper presented to the North-East Coast Institution of Engineers and Shipbuilders, Newcastle-upon-Tyne, April 1972.

33. Larkin, B.A. — *An Experimental Study of a Two-Phase Thermosiphon Tube.*
Canadian Society for Mechanical Engineering, Paper No. 70-CSME-6, September 1970.

34. — — *Combatting the Icing Problem.*
World Fishing, December 1968, p. 48

35. — — *De-icing Equipment for Trawlers.*
Sea Harvest and Ocean Science, December 1969/January 1970, p. 23.

36. Archibald, D.C. *Intense Storm Tracks over Hudson Bay, the Eastern Nova Scotia Coast and the Grand Banks.* Canadian Inst. Mining and Metallurgy, Special Vol. 10, "Ice Seminar", 1969, pp. 36-44.

37. — — *Oceanographic Atlas of the North Atlantic Ocean, Section II, Physical Properties.* U.S. Naval Oceanographic Office, Publication No. 700, 1967.

38. — — *State of Sea Photographs for the Beaufort Wind Scale.* Meteorological Branch, Dept. of Transport. The Queen's Printer, Ottawa, 1968.

39. List, R.J. *Smithsonian Meteorological Tables.* 6th Revised Edition, Smithsonian Institution, Washington, 1951.

40. Stallabrass, J.R. *Trawler Icing off Eastern Canada.* National Research Council Canada, Report No. LTR-LT-50, 1973.

41. — — *Recommendation on Intact Stability of Fishing Vessels.* Intergovernmental Maritime Consultative Organization, London, 1969.

42. Stallabrass, J.R. *Icing of Fishing Vessels: An Analysis of Reports from Canadian East Coast Waters.* National Research Council Canada, Report No. LTR-LT-98, 1979.

43. Guttman, N.B. *Study of Worldwide Occurrence of Fog, Thunderstorms, Supercooled Low Clouds and Freezing Temperatures.* National Oceanic and Atmospheric Administration (U.S.A.) for Naval Weather Service Command. NAVAIR-50-1C-60, December 1971.

44. — — *Large Fishing Vessel Inspection Regulations.* Queen's Printers, Ottawa, 1970.

45. Mertins, H.O. *Icing of Fishing Vessels due to Spray.* Marine Observer (London), Vol. 38, No. 221, 1968, pp. 128-130.

46. Comiskey, A. *Vessel Icing — Know when to Expect It.* Alaska Seas and Coasts, Vol. 4, No. 5, December 1976, pp. 6-7.

47. Kachurin, L.G., Gashin, L.I., Smirnov, I.A. *Icing Rate of Small Displacement Fishing Boats under Various Hydrometeorological Conditions.* Meteorologiya i Gidrologiya, Moscow, No. 3, 1974, pp. 50-60.

48. Oliver, R.C. *Trawlermen's Handbook.* Fishing News (Books) Ltd., 2nd Revised Edition, 1975.

49. Lewis, W., Brun, R.J. *Impingement of Water Droplets on a Rectangular Half Body in a Two-Dimensional Incompressible Flow Field.* U.S. National Advisory Committee for Aeronautics, Technical Note TN 3658, February 1956.

50. Hardy, J.K. *Evaporation of Droplets of Liquid.* Ministry of Supply (U.K.) A.R.C., R & M No. 2805, 1953.

51. Gunn, R., Kinzer, G.D. *The Terminal Velocity of Fall of Water Droplets in Stagnant Air.* Jour. of Meteorology, Vol. 6, 1949, pp. 243-248.

52. McAdams, W.H.1 — *Heat Transmission.* McGraw-Hill Book Co. In., 3rd Ed., 1954.

53. Rohsenow, W.M., Choi, H.Y. — *Heat, Mass, and Momentum Transfer.* Prentice-Hall, Inc., 1961.

54. Morgan, V.T. — *The Overall Convective Heat Transfer from Smooth Circular Cylinders.* In "Advances in Heat Transfer", Vol. 11, Ed. T.F. Irvin & J.P. Hartnett, Academic Press, 1975, pp. 199-264.

TABLE I

(Reproduced from Ref. 38)

Beaufort Force of Wind	Theoretical Max. Wave Height (ft), Unlimited Duration and Fetch	Duration of Winds (hours) with Unlimited Fetch, to Produce Percent of Max. Wave Height Indicated			Fetch (n. miles), with Unlimited Duration of Blow, to Produce Percent of Max. Wave Height Indicated		
		50%	75%	90%	50%	75%	90%
3	2	1.5	5	8	3	13	25
5	8	3.5	8	12	10	30	60
7	20	5.5	12	21	22	75	150
9	40	7	16	25	55	150	280
11	70	9	19	32	85	200	450

TABLE II

ICING QUESTIONNAIRE RESPONSE BY YEAR

Year	Number of Vessels Responding (A) and Number of Reports (including Null Reports) Received(B)							
	Fishing Vessels		Government Vessels[1]		Freighters, Tankers, etc.		Ferry Services	
	A	B	A	B	A	B	A	B
1968-69	2	2	3	3	1	1	—	—
1969-70	13	28	—	—	1	1	—	—
1970-71	29	89	—	—	—	—	—	—
1971-71	24	89	1	1	3	13	1	3
1972-73[2]	—	—	—	—	—	—	1	5
1973-74	29	119	—	—	1	2	1	1
1974-75[3]	5	8	15	43	8	8	1	40
1975-76	38	172	9	29	1	2	2	52
1976-77	35	124	10	28	3	5	4	70
1977-78	48	182	17	76	1	2	1	4
1978-79	22	73	13	20	—	—	—	—
Totals		886		200		34		175

Notes:

1. Government vessels include ice breakers, survey vessels, supply vessels, fishery patrol vessels, etc.
2. In year 1972-73 reports from Newfoundland were lost.
3. In year 1974-75 Newfoundland fishing fleets were on strike.

TABLE III

ICING SEVERITY STATISTICS FOR THE WHOLE STUDY AREA

	No. of Days Icing Severity Reported as:		
	Light or Greater	Moderate or Greater	Heavy
December			
7-year total	32	26	9
worst year	10	10	3
yearly average	4.6	3.7	1.3
standard deviation	3.5	3.2	1.0
daily expectation	14.7%	12.0%	4.1%
January			
7-year total	98	70	21
worst year	23	15	6
yearly average	14.0	10.0	3.0
standard deviation	4.5	3.0	1.6
daily expectation	45.2%	32.2%	9.7%
February			
7-year total	101	70	32
worst year	20	16	7
yearly average	14.4	10.0	4.6
standard deviation	3.4	3.7	2.4
daily expectation	51.0%	35.4%	16.2%
March			
7-year total	71	47	14
worst year	27	17	5
yearly average	10.1	6.7	2.0
standard deviation	8.9	5.8	1.9
daily expectation	32.7%	21.7%	6.5%
* * * * * * * *			
1 December — 31 March			
7-year total	302	213	76
worst year	72	50	15
yearly average	43.1	30.4	10.9
standard deviation	13.9	10.5	3.4
daily expectation	35.6%	25.1%	9.0%

TABLE IV

ICING SEVERITY STATISTICS FOR ICNAF DIVISION 3L

	No. of Days Icing Severity Reported as:		
	Light or Greater	Moderate or Greater	Heavy
December			
7-year total	7	5	5
worst year	3	3	3
yearly average	1.0	0.7	0.7
standard deviation	1.1	1.2	1.2
daily expectation	3.2%	2.3%	2.3%
January			
7-year total	33	24	9
worst year	11	8	3
yearly average	4.7	3.4	1.3
standard deviation	2.9	2.1	1.3
daily expectation	15.2%	11.1%	4.1%
February			
7-year total	30	11	2
worst year	8	4	1
yearly average	4.3	1.6	0.3
standard deviation	1.9	1.4	0.5
daily expectation	15.2%	5.6%	1.0%
March			
7-year total	27	21	4
worst year	12	8	2
yearly average	3.9	3.0	0.6
standard deviation	3.9	2.9	0.7
daily expectation	12.4%	9.7%	1.8%
* * * * * * * *			
1 December — 31 March			
7-year total	97	61	20
worst year	34	20	5
yearly average	13.9	8.7	2.9
standard deviation	8.8	5.3	1.8
daily expectation	11.4%	7.2%	2.4%

TABLE V

ICING SEVERITY STATISTICS FOR ICNAF DIVISION 3P

	No. of Days Icing Severity Reported as:		
	Light or Greater	Moderate or Greater	Heavy
December			
7-year total	4	3	0
worst year	2	2	0
yearly average	0.6	0.4	0
standard deviation	0.7	0.7	0
daily expectation	1.8%	1.4%	0%
January			
7-year total	53	38	10
worst year	11	8	3
yearly average	7.6	5.4	1.4
standard deviation	3.0	2.7	1.2
dialy expectation	24.4%	17.5%	4.6%
February			
7-year total	59	41	18
worst year	16	12	4
yearly average	8.4	5.9	2.6
standard deviation	3.6	3.1	1.3
daily expectation	29.8%	20.7%	9.1%
March			
7-year total	38	23	4
worst year	14	7	3
yearly average	5.4	3.3	0.6
standard deviation	5.2	2.8	1.0
daily expectation	17.5%	10.6%	1.8%

* * * * * * * *

1 December — 31 March			
7-year total	154	105	32
worst year	37	27	7
yearly average	22.0	15.0	4.5
standard deviation	8.3	6.3	1.7
daily expectation	18.1%	12.4%	3.8%

TABLE VI

SUMMARY OF ICING ENCOUNTERS IN TERMS OF IMCO STANDARD ICING ALLOWANCE

Icing Season	Total Voyages	Degree of Icing								
		No Ice	Slight	½ IMCO	IMCO	1½ IMCO	2 IMCO	2½ IMCO	3 IMCO	3½ IMCO
1970-71	88 100%	54 61%	17 19%	7 8%	3 3%	1 1%	4 5%	1 1%	1 1%	— —
1971-72	87 100%	52 60%	12 15%	5 6%	6 6%	4 5%	2 2%	4 5%	2 2%	— —
1973-74	105 100%	61 58%	18 17%	9 9%	4 4%	5 5%	4 4%	1 1%	2 2%	1 1%
1975-76	173 100%	93 54%	17 10%	38 22%	18 10%	5 3%	2 1%	— —	— —	— —
1976-77	78 100%	59 76%	1 1%	9 12%	4 5%	1 1%	2 3%	2 3%	— —	— —
1977-78	78 100%	43 55%	8 10%	13 17%	9 12%	2 3%	1 1%	2 3%	— —	— —
1978-79	52 100%	38 73%	2 4%	3 6%	3 6%	3 6%	2 4%	1 2%	— —	— —
7-year total	661 100%	400 61%	76 11%	84 13%	46 7%	21 3%	17 2.6%	11 1.7%	5 0.8%	1 0.2%

8% exceed IMCO standard allowance.
2.5% exceed twice IMCO standard allowance.

TABLE VII

NUMBER (AND PERCENTAGE) OF YEARS FOR WHICH AT LEAST ONE OCCURRENCE OF ICING OF SEVERITY GREATER THAN SLIGHT HAS BEEN REPORTED FOR THE DESIGNATED ICNAF DIVISION IN EACH OF THE WINTER MONTHS

ICNAF Division	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1F			1 (13%)			
2G			1 (13%)			
2H	1 (13%)		2 (25%)		1 (13%)	
2J	3 (38%)		3 (38%)	3 (38%)	1 (13%)	
3K	2 (25%)	1 (13%)	4 (50%)	4 (50%)	2 (25%)	
3L	1 (13%)	2 (25%)	7 (88%)	7 (88%)	4 (50%)	
3M						
3N			1 (13%)	2 (25%)		
3O		1 (13%)	2 (25%)	5 (63%)	2 (25%)	
3P		3 (38%)	8 (100%)	8 (100%)	6 (75%)	2 (25%)
4R	1 (13%)	2 (25%)	5 (63%)	4 (75%)	1 (13%)	2 (25%)
4S			3 (38%)	4 (50%)	1 (13%)	1 (13%)
4T		2 (25%)	2 (25%)	3 (38%)		1 (13%)
4Vn*		4 (50%)	8 (100%)	6 (75%)	3 (38%)	2 (25%)
4Vs*						
4W		4 (50%)	4 (50%)	7 (88%)	2 (25%)	
4X		3 (38%)	5 (63%)	4 (50%)	3 (38%)	
5Y		1 (13%)	1 (13%)	2 (25%)	1 (13%)	

Based on 8 years of data

* The boundary between 4Vn and 4Vs is here taken to be the parallel 44° 10′ N instead of 45° 40′ N.

TABLE VIII

DATA USABLE FOR ICING RATE STUDIES
FROM SEASONS 1977-78 AND 1978-79

(1) Data Set No.	(2) Vessel Length m	(3) Rel. Wind Velocity kt	(4) Air Temp. °C	(5) Sea-Surf. Temp. °C	(6) Wave Height m	(7) Sea Salinity ‰	(8) Icing Rate mm/h	(9) Calculated Icing Rate (Eq. B.3/c) mm/hr
1	51.5	55	−6	+1	5*	32.25	8.5	5.1
2	51	35	−3.5†	−0.5	1.2	31	1.6	2.1
3	51	35	−6 †	+4	3*	32.35	0.79	3.3
4	51	48	−3	−0.5	4.5*	34	4.2	1.6
5	51	32	−5	−1	1	33.75	1.3	3.0
6	51	56	−4	−2	3*	33.25	0.75	4.2
7	51	36	−7 †	+1	3*	32.25	10.9	5.3
8	51	39	−4	0	3*	32.7	3.2	2.6
9	51	32	−10 †	+2	9	33.75	4.8	7.3
10	47	36	−2	0	0.6*	31.5	4.8	0.65
11	47	25	−5	0	2.4*	34	0.85	2.7
12	47	40	−9 †	0	2.4	32.5	0.71	7.9
13	47	40	−6.5	+0.5	3*	32.75	2.8	5.2
14	47	50	−4	−1	3*	32.3	5.4	3.5
15	47	55	−8	+1	3*	32.3	1.6	8.2
16	46	38	−8 †	+1.5	2	31	3.8	6.3
17	44	45	−14	−0.5	3*	32.75	12.7	14.1
18	44	35	−5.5	+4	1	32.1	3.0	3.3
19	44	28	−3	+1	2*	32	1.8	1.2
20	44	28	−10	0	2*	31	7.3	6.8
21	42	37	−10	−0.5	2*	33.5	3.6	8.2
22	42	26	−5	0	1*	31	2.6	2.6
23	42	25	−5	0	1*	33.5	2.1	2.4
24	42	25	−5	+3	3*	34	1.9	2.2
25	42	25	−6	0	1.5	31	8.0	3.4
26	42	33	−10	+1.5	2	32.5	3.5	7.3
27	42	38	−12	+2	1.5	32.25	6.5	9.5
28	42	30	−10	0	1.2	32	6.9	6.6
29	42	39	−16	0	1.2	33.75	10.6	12.8
30	38	41	−7	−1	3*	32.25	1.6	6.4
31	34	26	−10 †	0	3*	31	2.4	6.8
32	34	32	−7 †	−1	3*	32	2.2	5.4

TABLE VIII (Cont'd)

DATA USABLE FOR ICING RATE STUDIES
FROM SEASONS 1977-78 AND 1978-79

(1) Data Set No.	(2) Vessel Length m	(3) Rel. Wind Velocity kt	(4) Air Temp. °C	(5) Sea-Surf. Temp. °C	(6) Wave Height m	(7) Sea Salinity ‰	(8) Icing Rate mm/h	(9) Calculated Icing Rate (Eq.B.3/c) mm/hr
33	51	46	-6 †	0	2	32.25	4.0	5.3
34	51	21	-10	-0.5	3*	33.25	3.9	5.8
35	47	29	-5	+0.5	2	33.5	2.8	2.9
36	44	31	-6	0	2*	32.3	1.9	4.0
37	42	35	-6	-0.5	3*	32.5	2.1	4.6
38	42	19	-4	0	2*	32.2	1.6	1.7
39	38	31	-5	+2	3	31	2.5	2.9

Data in Columns (3), (4),(6) and (8) derived from Ship Icing Reports

† These air temperatures inferred from other vessels in same general vicinity.

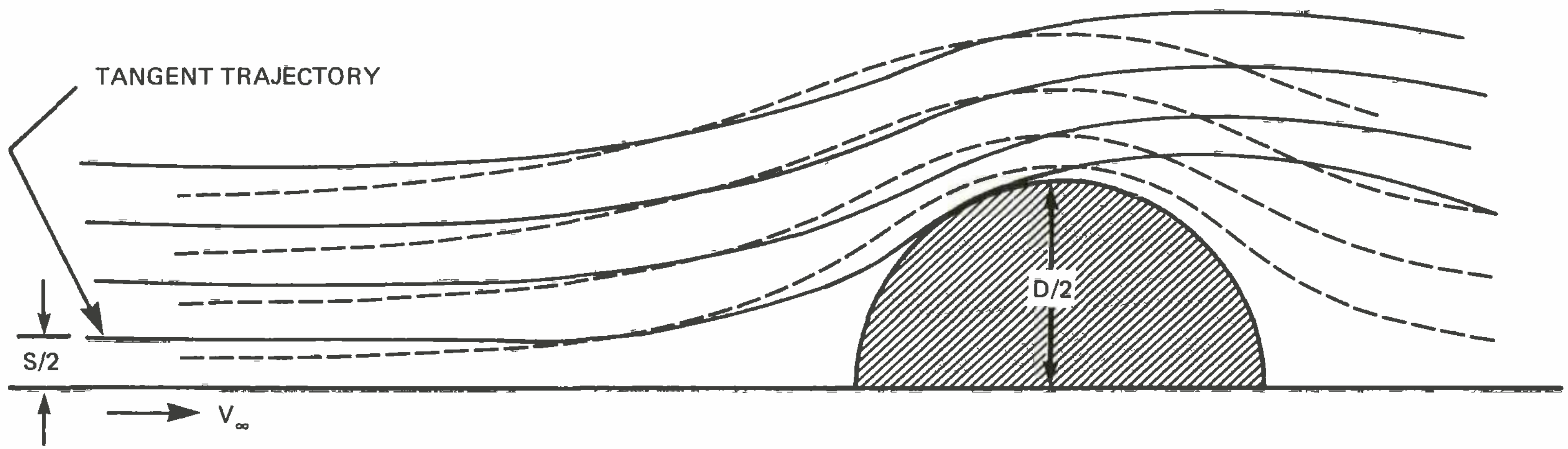
* These wave heights inferred from sea state description.

IN DATA SETS 1 TO 32 THE RELATIVE WIND DIRECTION IS 0° ±45°.

DATA SETS 33 to 39 HAVE RELATIVE WIND DIRECTION $>$ 45°.

S = DISTANCE BETWEEN UPPER AND LOWER TANGENT TRAJECTORIES IN UNDISTURBED FLOW AHEAD OF CYLINDER.

D = CYLINDER DIAMETER.

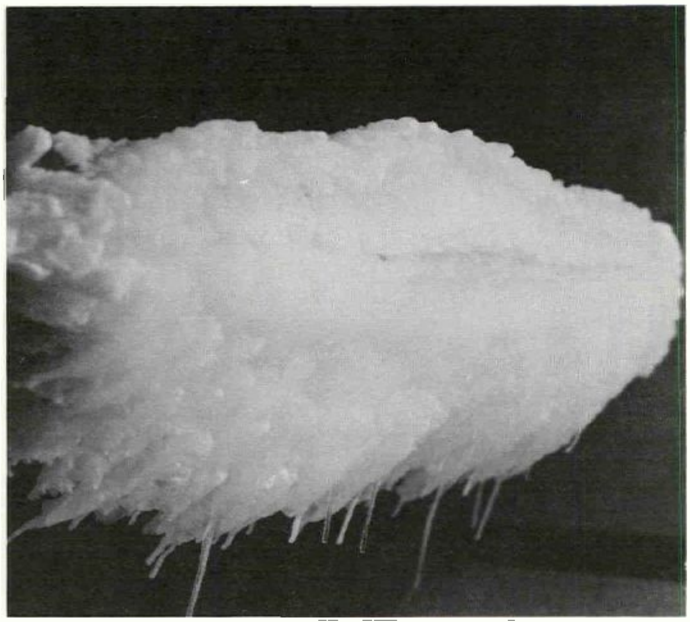


——— WATER DROP TRAJECTORIES

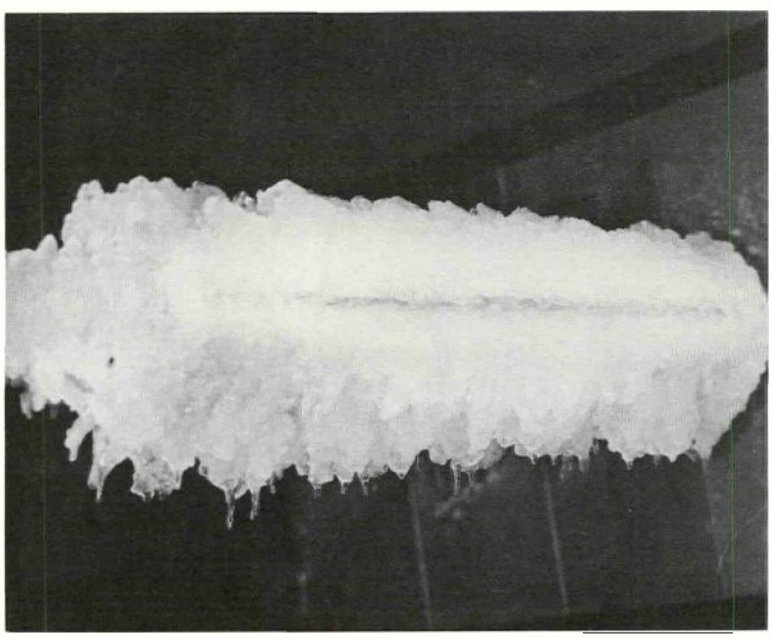
- - - - STREAMLINES

COLLECTION EFFICIENCY $E_m = \frac{S}{D}$

FIG. 1: WATER DROP TRAJECTORIES IN THE VICINITY OF A CIRCULAR CYLINDER

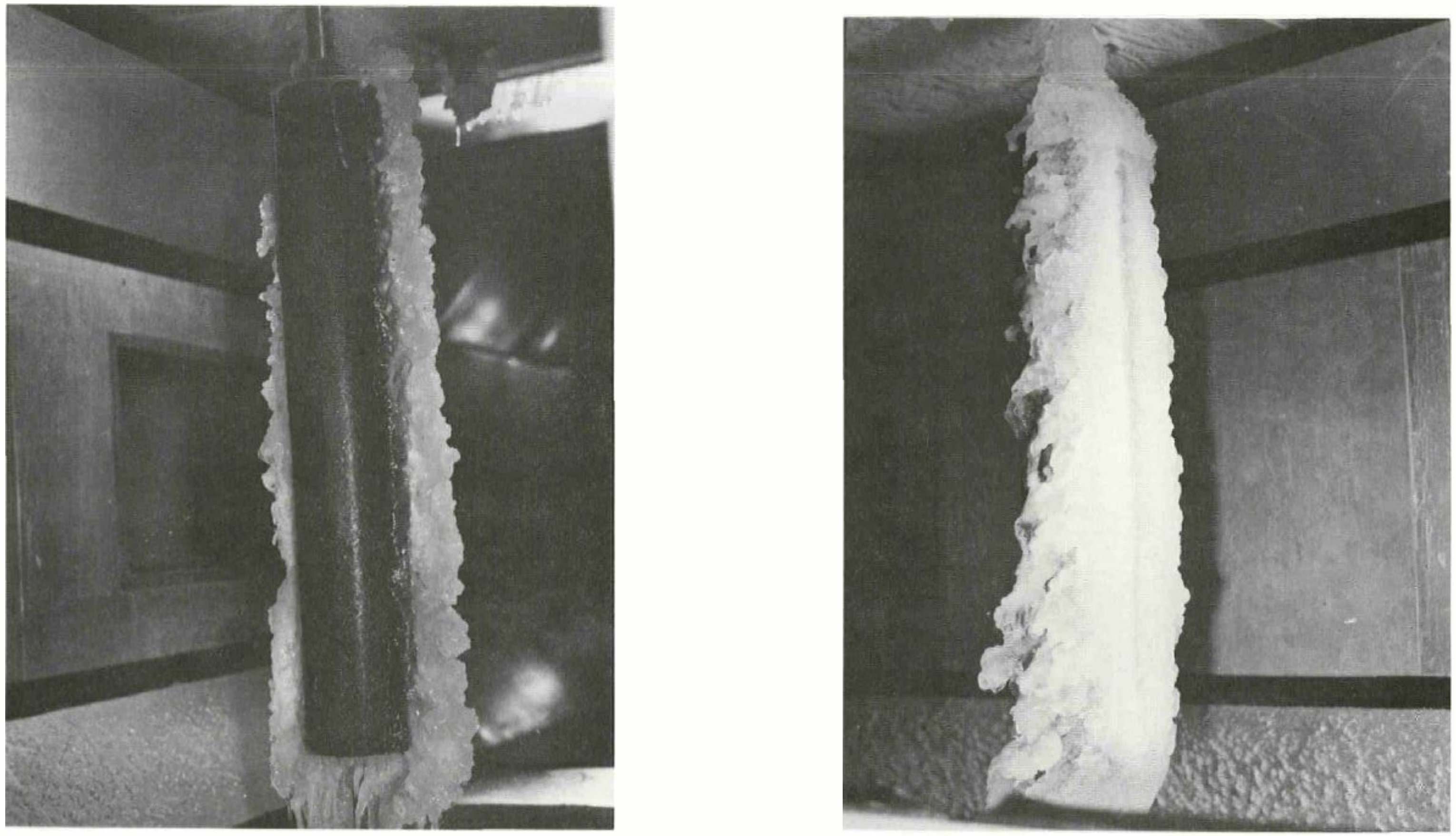


AIR TEMPERATURE: −16°C. (RUN NO. 5)



AIR TEMPERATURE: −7.5°C. (RUN NO. 6)

FIG. 2: ICE ACCRETIONS ON 15.2 CM HORIZONTAL CYLINDER AFTER 1 HOUR EXPOSURE



BACK FRONT

AIR TEMPERATURE: -6.0°C.

FIG. 3: ICE ACCRETIONS ON 15.2 CM VERTICAL CYLINDER AFTER 1 HOUR EXPOSURE
RUN NO. 16

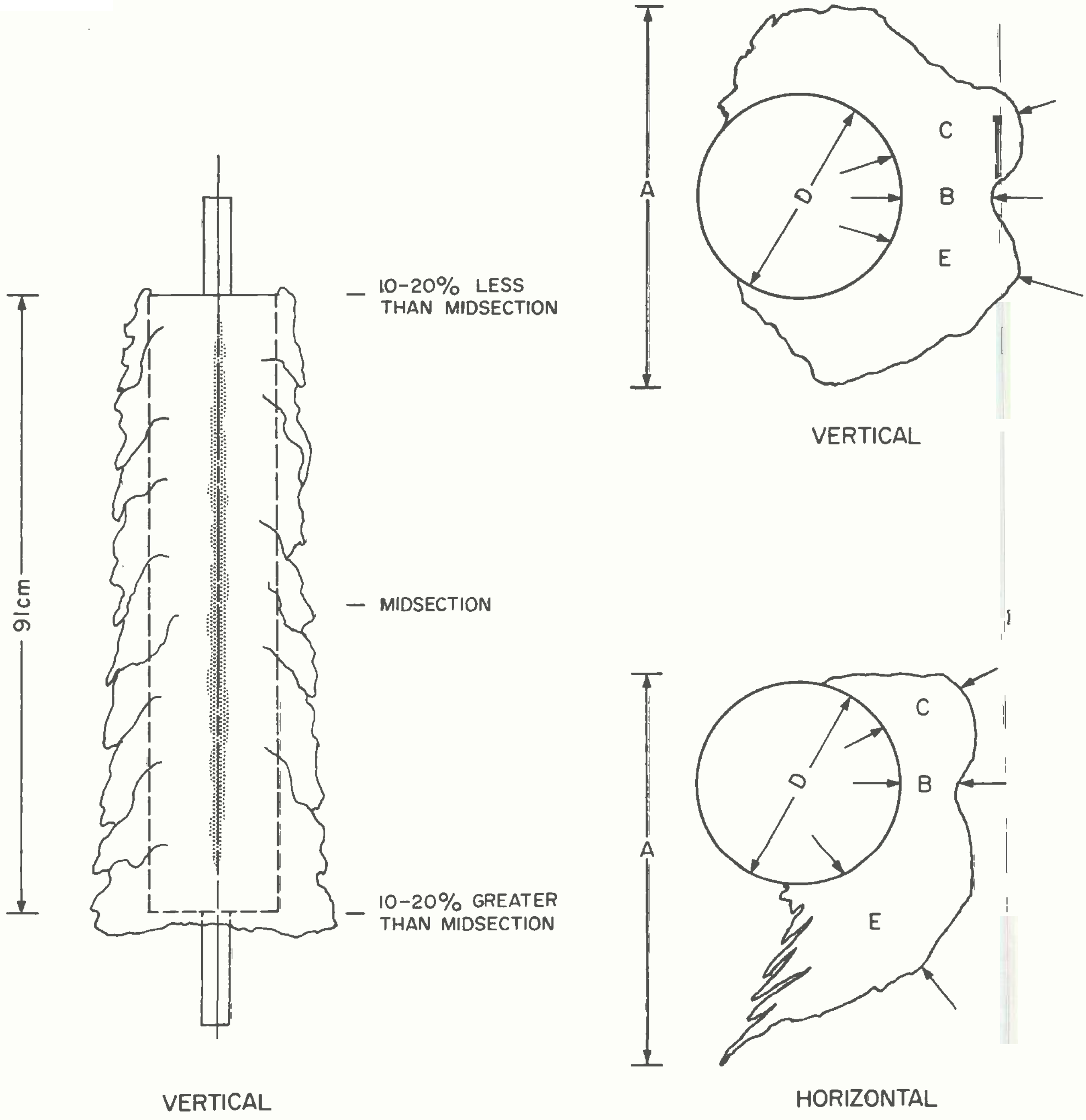


FIG. 4: DIMENSIONS OF ICE ON VERTICAL AND HORIZONTAL CYLINDERS

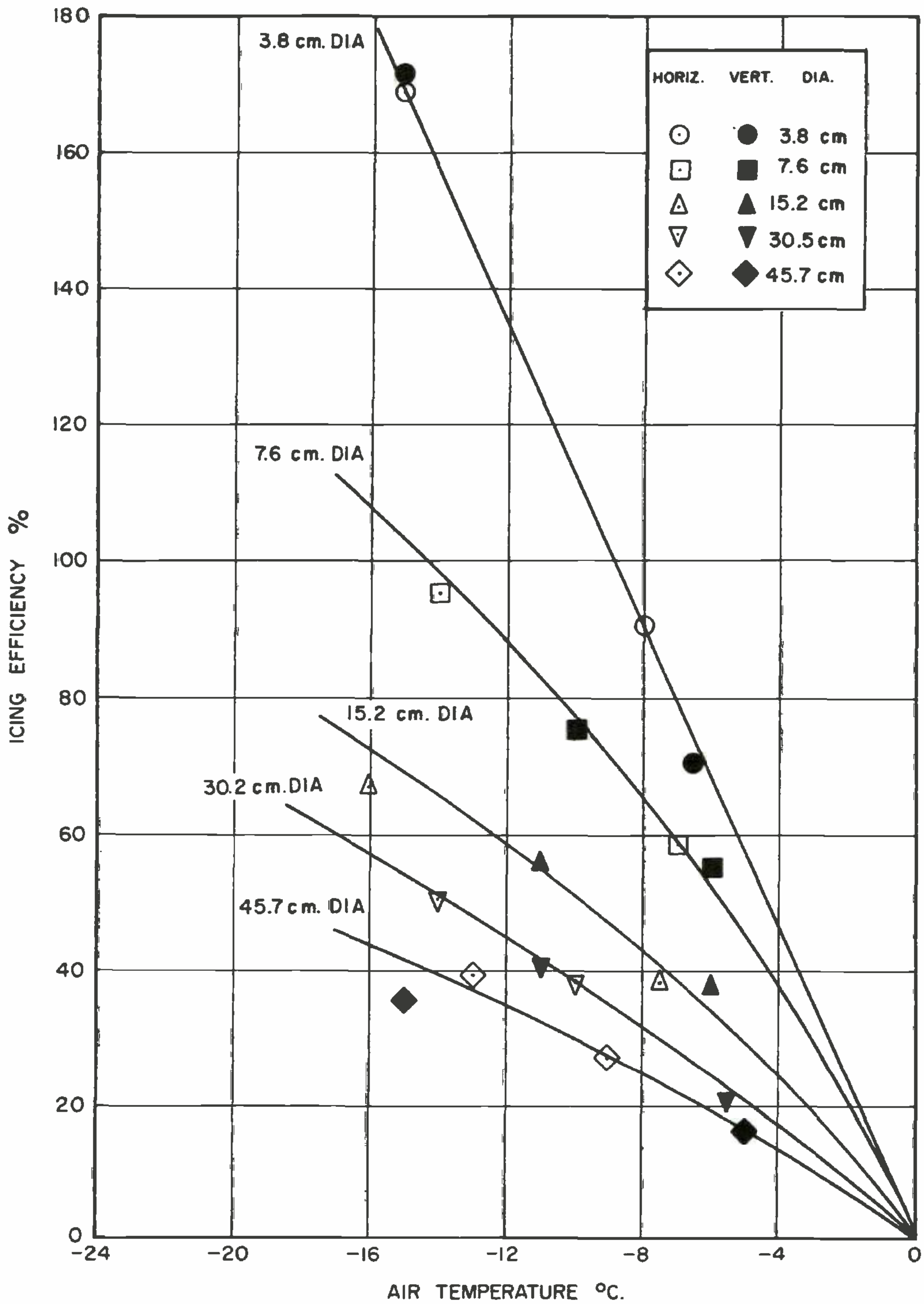


FIG. 5: EFFECT OF TEMPERATURE ON ICING EFFICIENCY

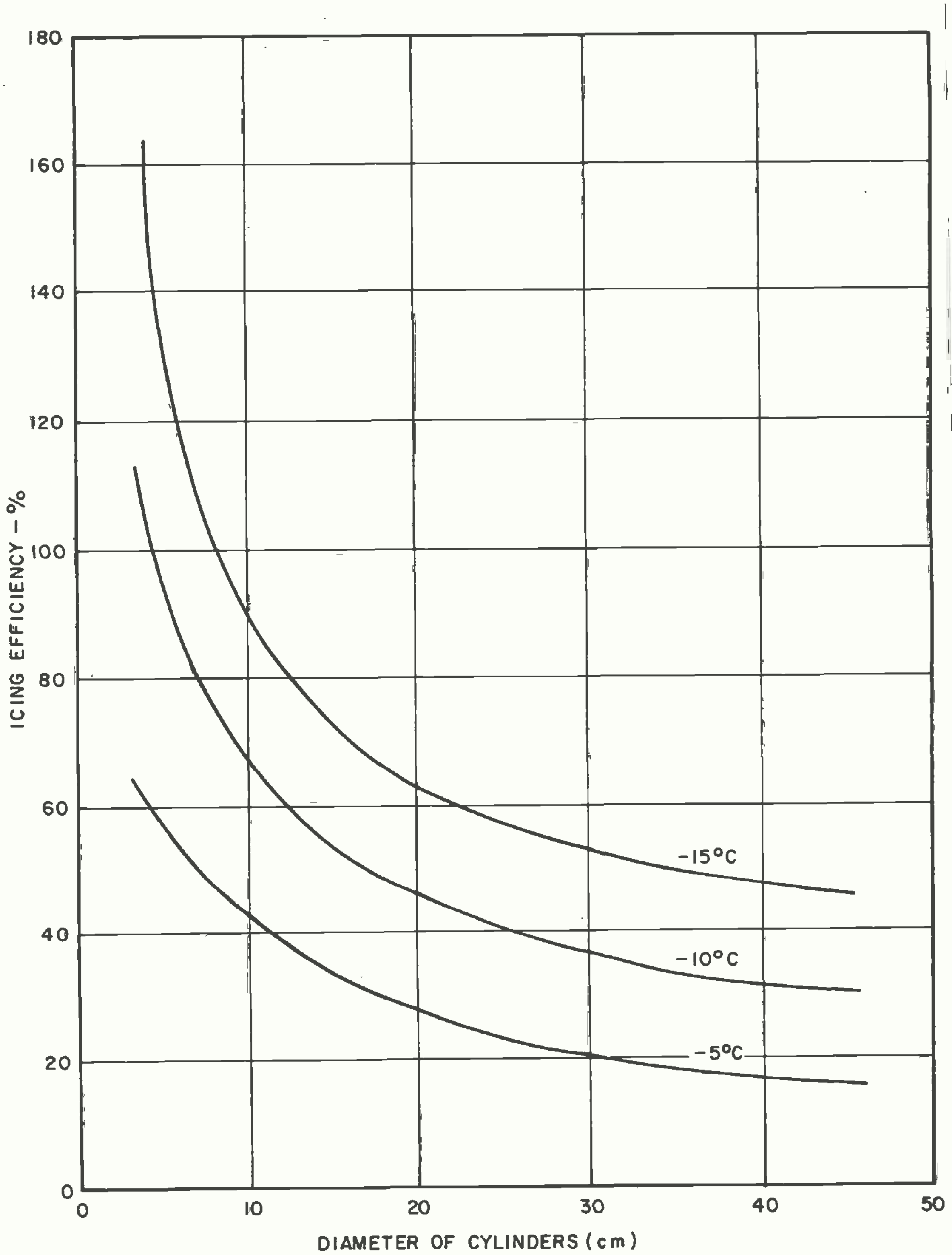


FIG. 6: EFFECT OF CYLINDER DIAMETER ON ICING EFFICIENCY
TRANSPOSED FROM FIG. 5

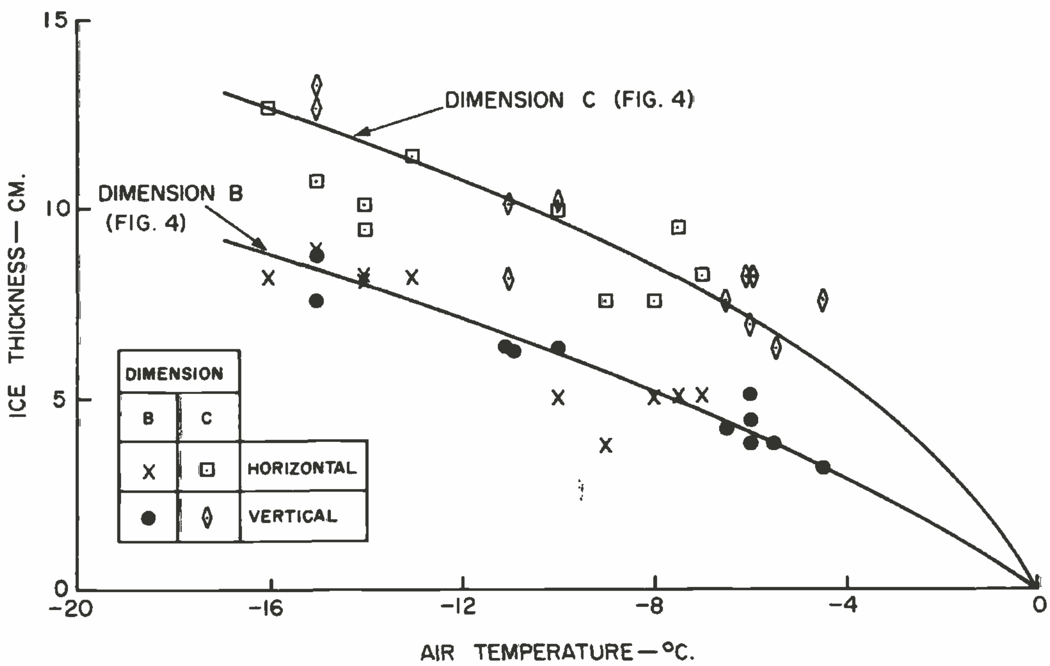


FIG. 7(a): EFFECT OF TEMPERATURE ON ICE THICKNESS

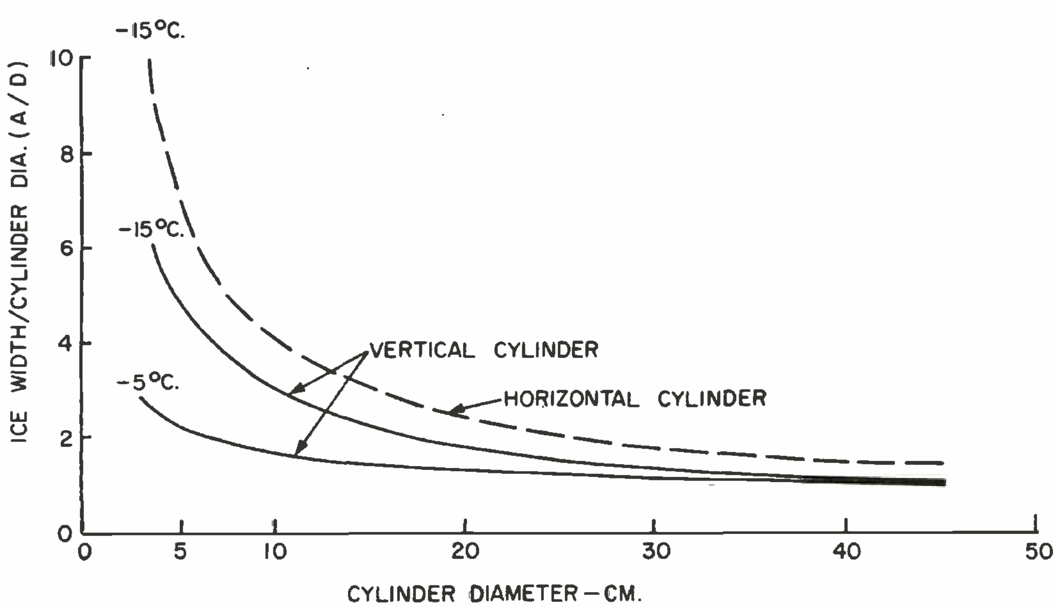


FIG. 7(b): EFFECT OF CYLINDER DIAMETER ON ICE WIDTH

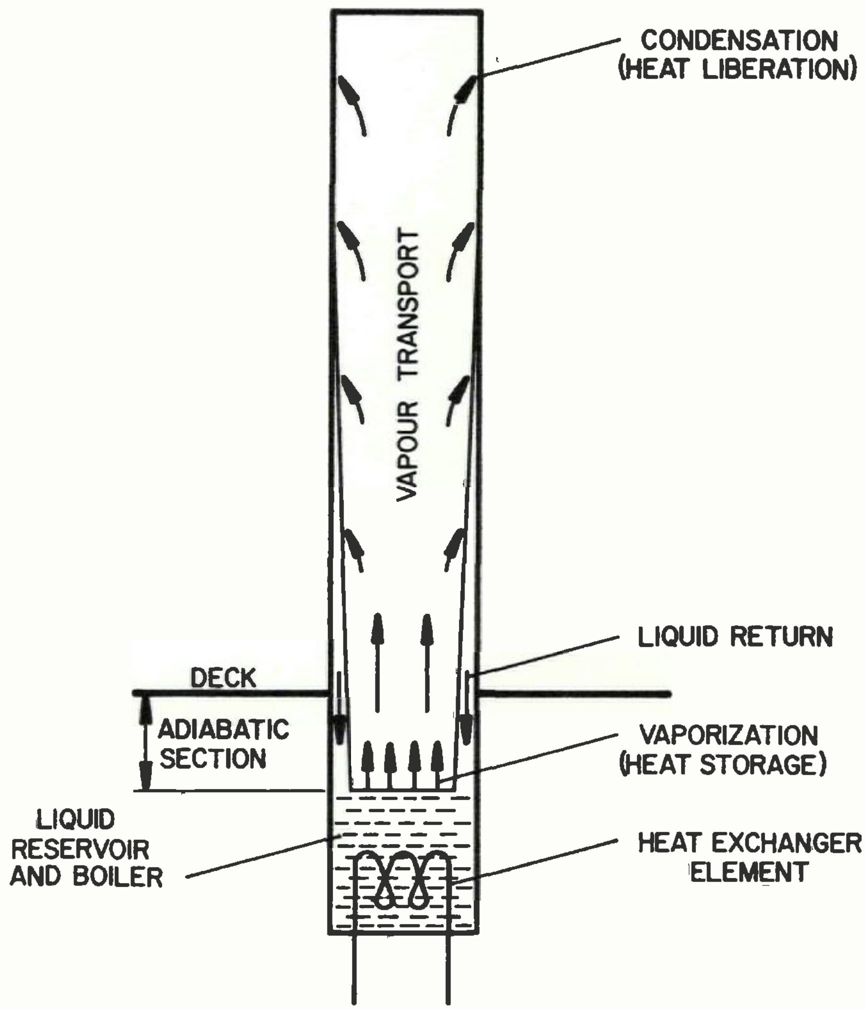


FIG. 8: TWO-PHASE THERMOSYPHON

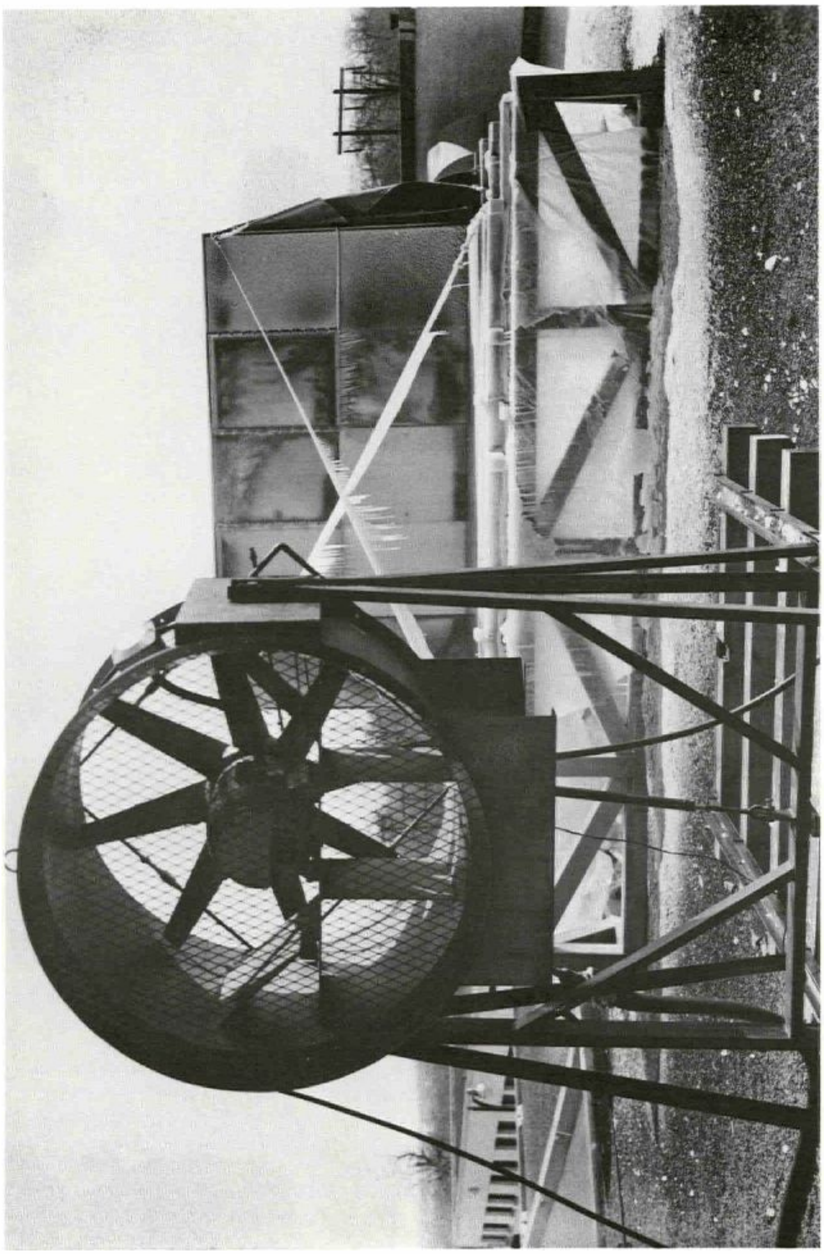
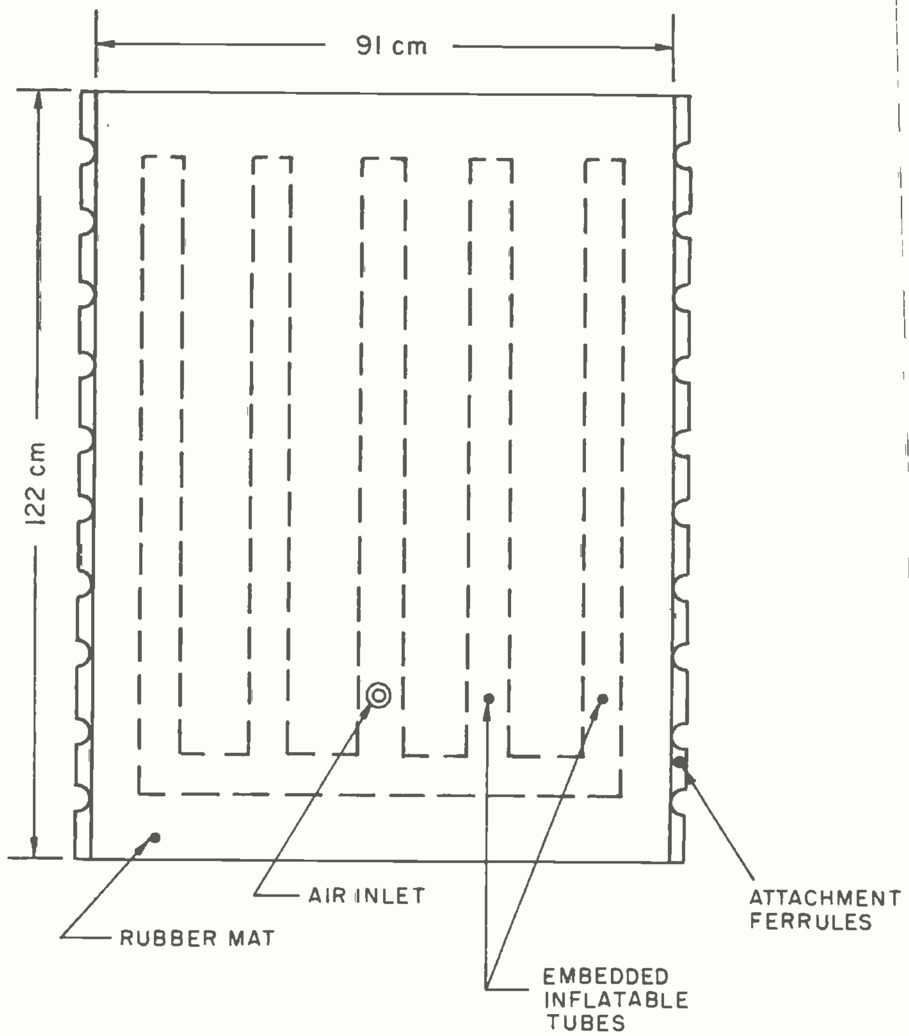
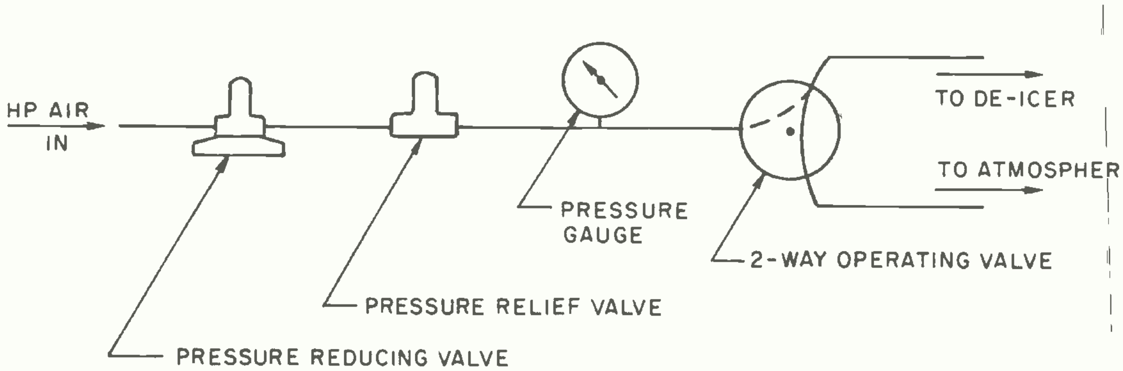


FIG. 9: OUTDOOR ICING TEST FACILITY



(a) LAYOUT OF PNEUMATIC DE-ICER



(b) CONTROL GEAR

FIG. 10: DETAILS OF PNEUMATIC DE-ICER

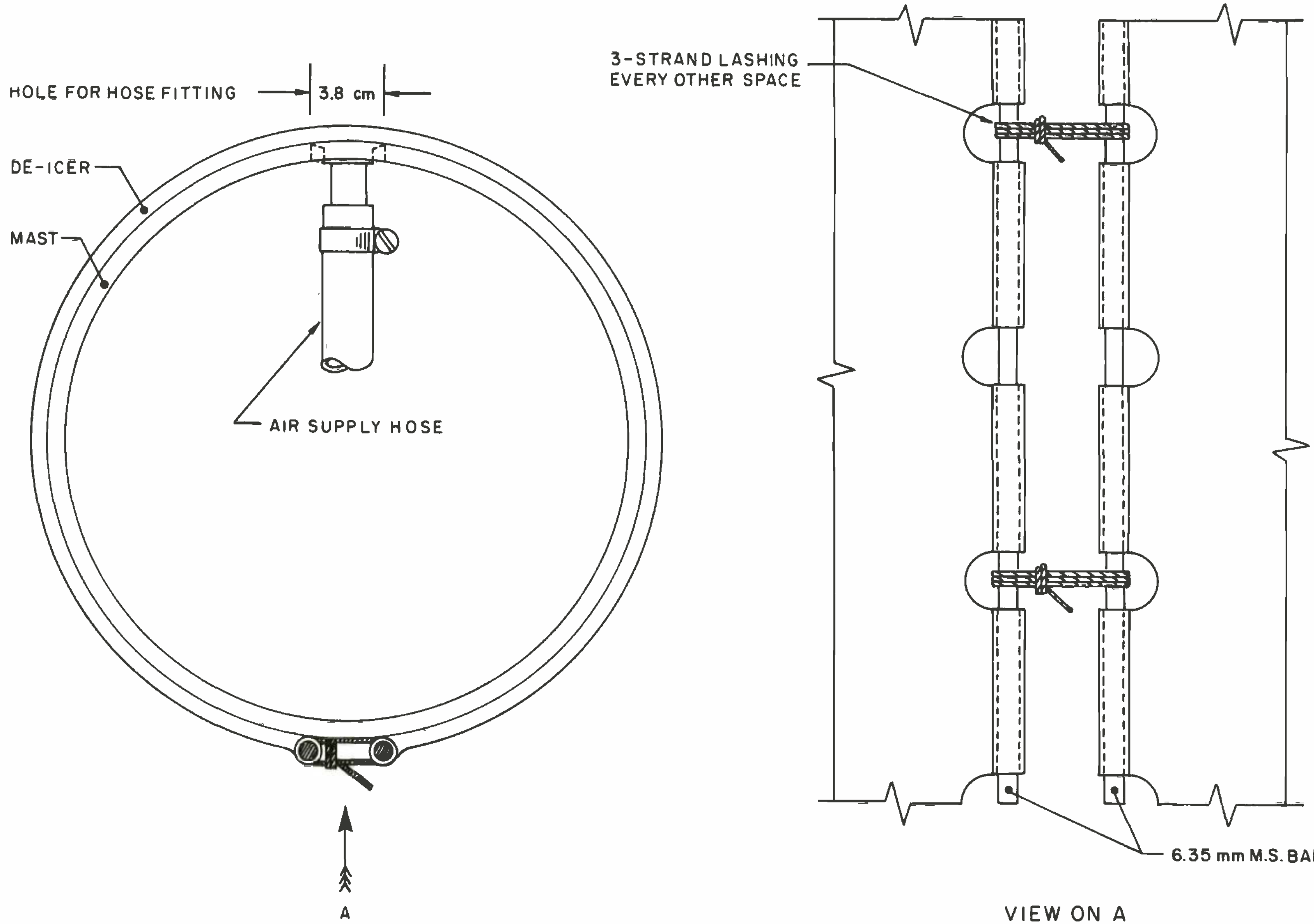
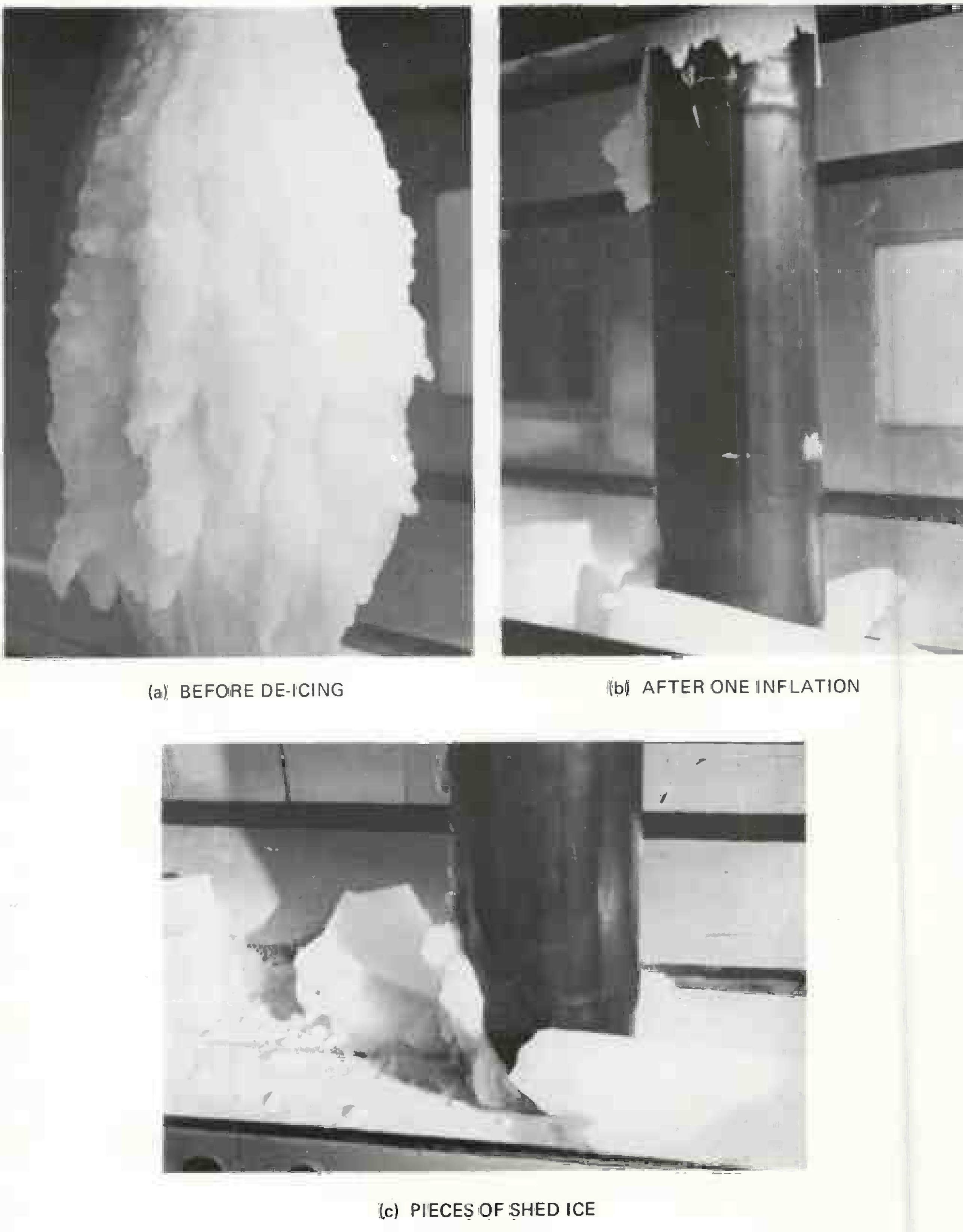


FIG. 11: METHOD OF ATTACHMENT OF PNEUMATIC DE-ICER TO MAST



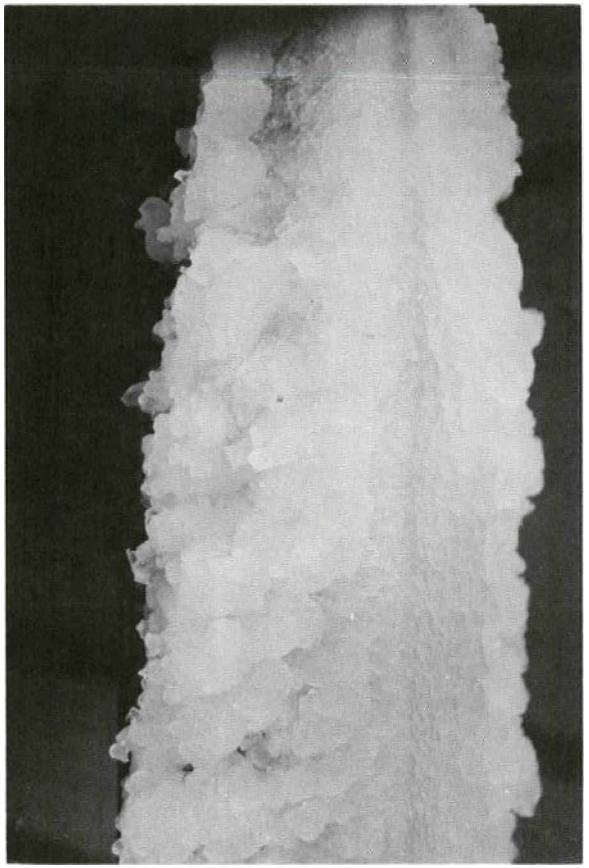
(a) BEFORE DE-ICING

(b) AFTER ONE INFLATION

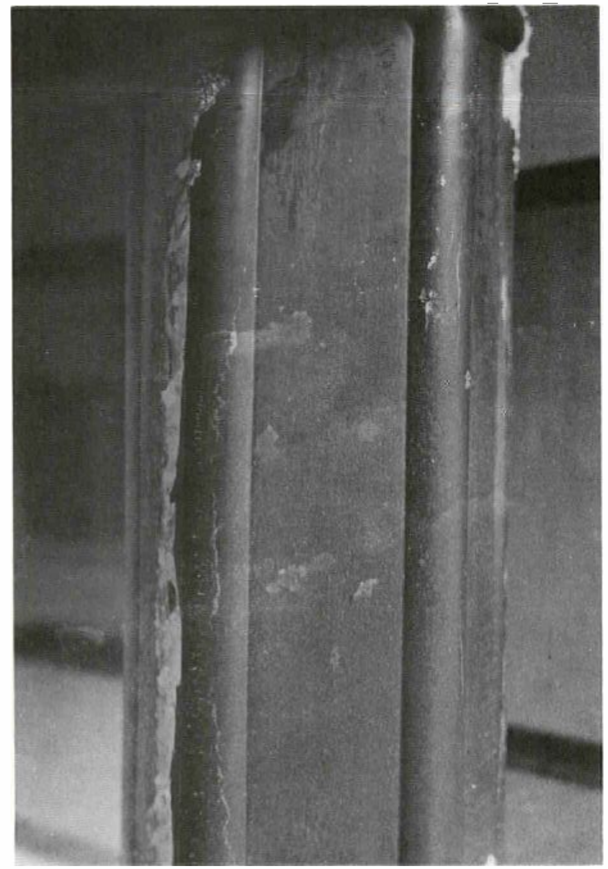
(c) PIECES OF SHED ICE

FIG. 12: PNEUMATIC MAST DE-ICER — DE-ICING SEQUENCE AFTER WIND TUNNEL RUN NO. 2

TEMPERATURE: −23°C   ICE THICKNESS: UP TO 13 cm   DE-ICER AIR PRESSURE: 100 kPa



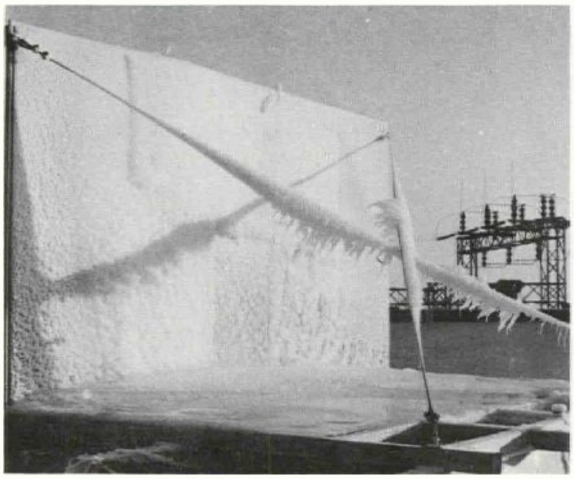
(a) BEFORE DE-ICING



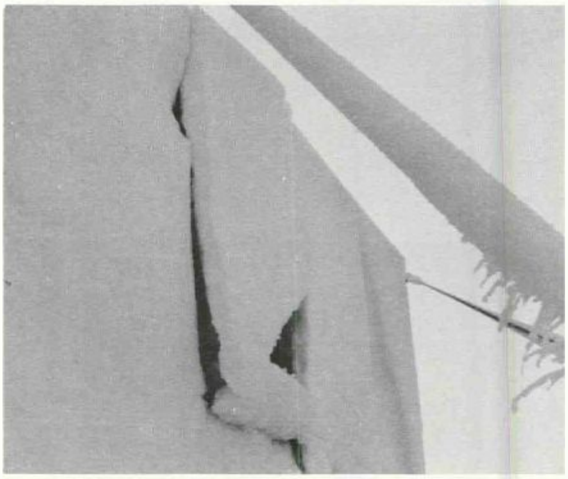
(b) DE-ICER INFLATED

FIG. 13: PNEUMATIC MAST DE-ICER – DE-ICING SEQUENCE AFTER WIND TUNNEL RUN NO. 4

TEMPERATURE: −10°C   ICE THICKNESS: UP TO 9 cm   DE-ICER AIR PRESSURE: 70 kPa

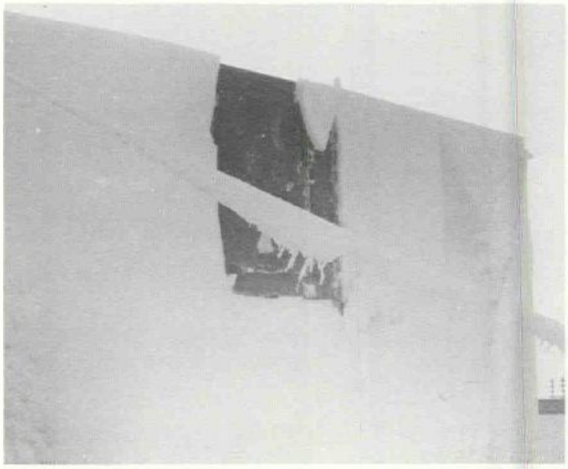


(a) AT CONCLUSION OF ICING



(b) AFTER TWO INFLATIONS OF DE-ICER

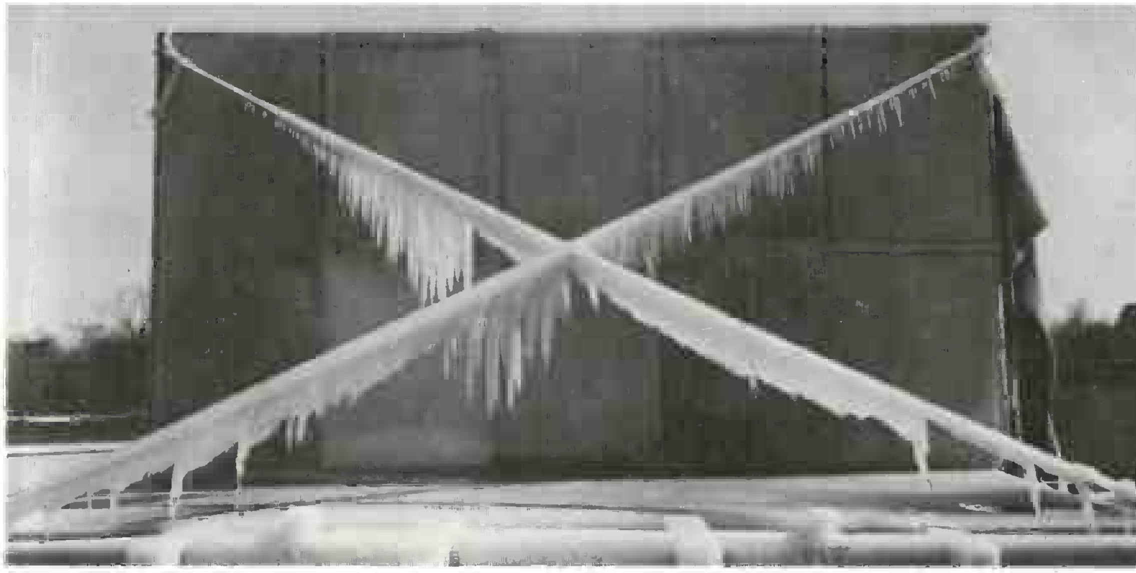
(c) AFTER TWO INFLATIONS OF DE-ICER



(d) AFTER THIRD INFLATION

FIG. 14: OUTDOOR TEST NO. 2

ICING TEMPERATURE: −15°C
DE-ICED AT −19°C AFTER 17 HOURS COLD SOAK



(a) AT CONCLUSION OF ICING

(b) AFTER OPERATION OF DE-ICERS

FIG. 15: OUTDOOR TEST NO. 6

ICING TEMPERATURE: $-15^{\circ}C$

DE-ICED AT $-12^{\circ}C$

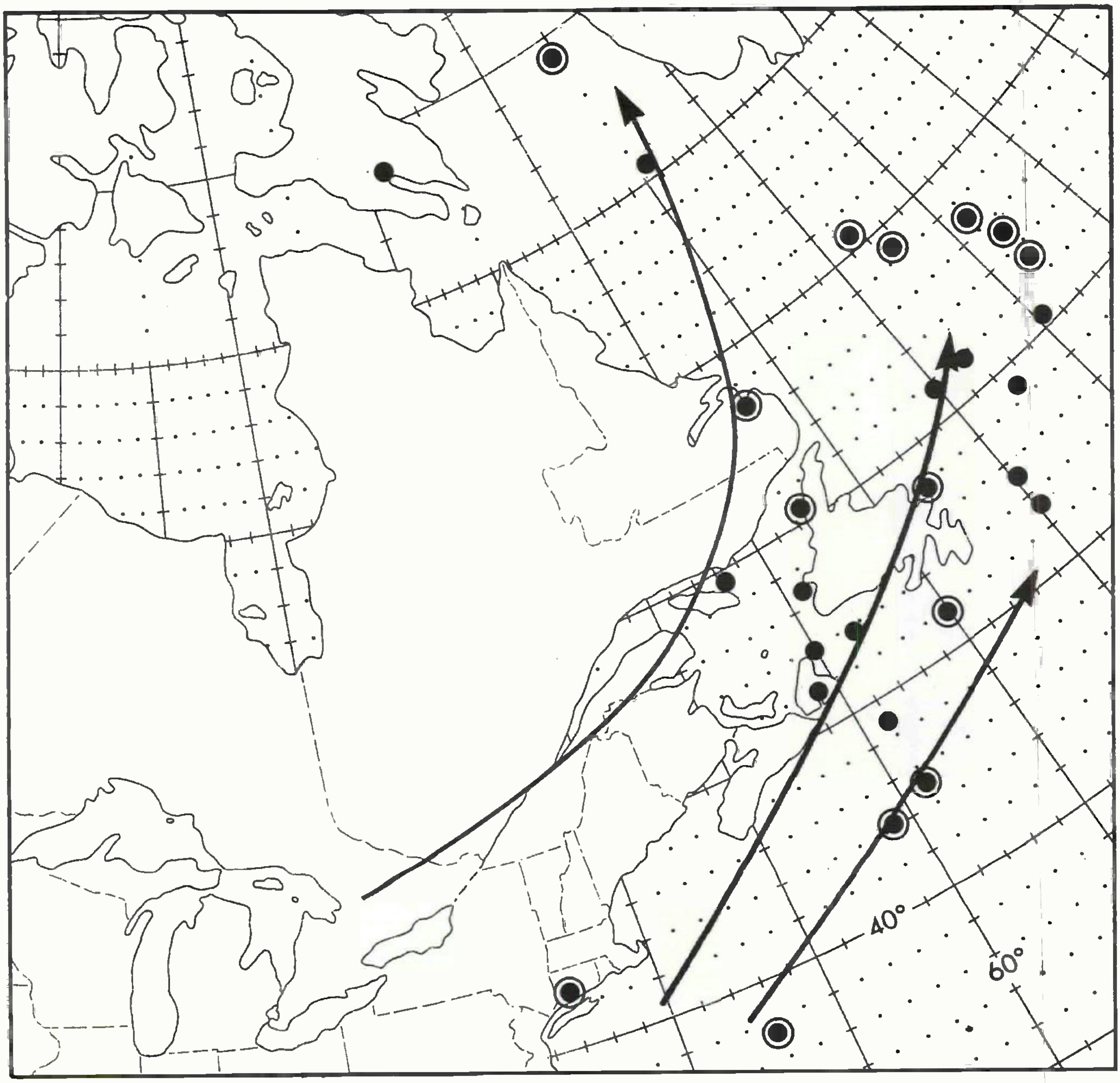


FIG. 16: PRINCIPLE TRACKS OF INTENSE STORMS FOR JANUARY, FEBRUARY AND MARCH 1963-67
(FROM ARCHIBALD, Ref. 36)

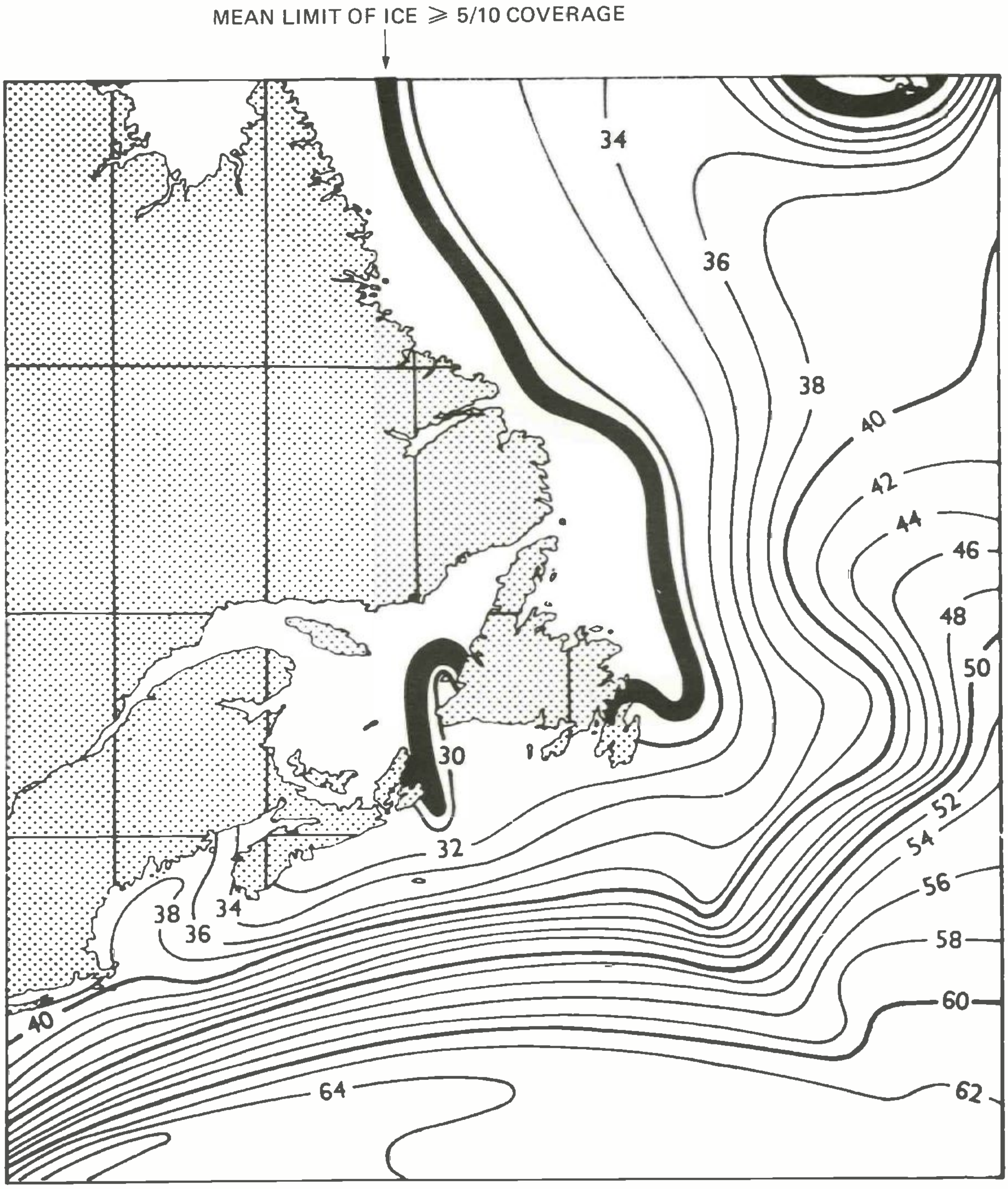


FIG. 17: MEAN SEA-SURFACE TEMPERATURE (°F) FOR FEBRUARY
(FROM OCEANOGRAPHIC ATLAS – REF. 37)

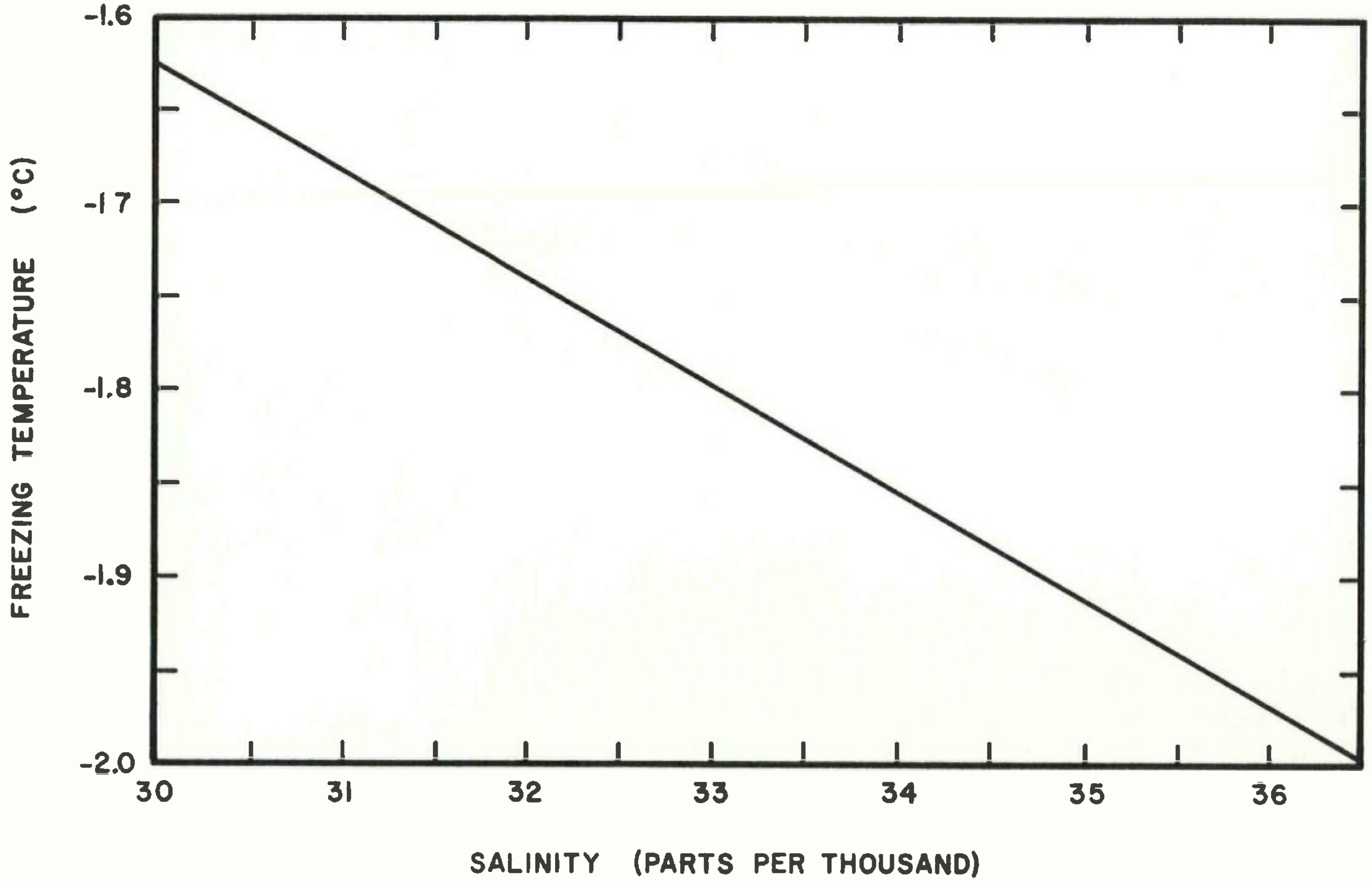


FIG. 18: FREEZING TEMPERATURE OF SEA WATER AS A FUNCTION OF SALINITY

Transport Canada / Transports Canada

SHIP ICING REPORT

PLEASE REPORT ON THIS FORM ANY INSTANCE OF ICE FORMATION ON VESSEL DURING VOYAGE. IF MORE THAN ONE OCCURRENCE OF ICING ON VOYAGE, USE SEPARATE FORM FOR EACH ENCOUNTER. IT IS IMPORTANT TO COMPLETE A FORM FOR EACH VOYAGE EVEN IF NO ICING OCCURS.

Name of ship:	Type of vessel:
Owner:	Home port:

DATE OF VOYAGE

Start:	Finish:

1. ROUTE OR AREA OPERATIONS –

State route or area –	Was icing encountered? – Yes ☐ No ☐

State where icing was encountered, give lat. & long., Decca or Loran fixes or distance and bearing from known point of land.

Give date and time (local) when icing commenced –

Date	Stopped

2. WEATHER CONDITIONS DURING ICING:

Weather (rain, snow, etc.) –	Wind (speed & direction) –

Sea state and wave height	Air temp.	Sea temp.

3. While ice was forming, was vessel steaming? ☐ Speed Heading

fishing? ☐

dodging? ☐

other? ☐ Comment:

4. Severity of icing estimated as: ☐ Trace ☐ Light ☐ Moderate ☐ Heavy

5. INDICATE AVERAGE ICE THICKNESS AT VARIOUS LOCATIONS WHEN BUILD-UP IS GREATEST:

	0 - 1 in. 0 - 25 mm	1 - 2 in. 25 - 50 mm	2 - 3 in. 50 - 75 mm	3 - 5 in. 75 - 100 m	Greater than 5 in. - 100 mm Specify if desired
(a) Diameter of ice on forward rails		☐	☐	☐	☐
(b) Diameter of ice on other rails		☐	☐	☐	☐
(c) Diameter of ice on forward stay		☐	☐	☐	☐
(d) Thickness on main deck	☐	☐	☐	☐	☐
(e) Thickness on boat deck	☐	☐	☐	☐	☐
(f) Thickness on wheel house front	☐	☐	☐	☐	☐
(g) Thickness on bulwarks	☐	☐	☐	☐	☐
(h) Other specify	☐	☐	☐	☐	☐

6. To what height did ice extend on forward mast? Feet / Metres above main deck	7. Total weight of ice on vessel estimated as Tons

8. Was handling affected by icing? Yes ☐ No ☐ Comments such as rolling time and amount of heel would be helpful.	9. Additional comments:

COMPLETED FORMS SHOULD BE MAILED TO: LOW TEMPERATURE LABORATORY, DIVISION OF MECHANICAL ENGINEERING, NATIONAL RESEARCH COUNCIL, OTTAWA, ONTARIO K1A 0R6

INCHES: 0 1 2 3 4 5

MILLIMETER: 0 10 20 30 40 50 60 70 80 90 100 110 120 130

85-0273 (11-77)

Français au verso

FIG. 19: SHIP ICING REPORT FORM

	0-1 in. 0-25 mm	1-2 in. 25-50 mm	2-3 in. 50-75 mm	3-5 in. 75-100 mm	over 5 in. over 100 mm
(a) Diameter of ice on forward rails		1	2	4	8
(b) Diameter of ice on other rails		2	4	8	12
(c) Diameter of ice on forward stay		1	2	4	8
(d) Thickness on main deck	2	4	8	12	20
(e) Thickness on boat deck	2	4	8	12	20
(f) Thickness on wheel house front	2	4	8	12	20
(g) Thickness on bulwarks	2	4	8	12	20

IMCO Rating	slight	½	1	1½	2	2½	3	3½	4
RANGE	0-7	8-20	21-35	36-48	49-63	64-76	77-91	92-104	105 up

FIG. 20: ARBITRARY POINTS SYSTEM USED TO RELATE REPORTED ICE THICKNESS TO IMCO ICING ALLOWANCE CRITERION

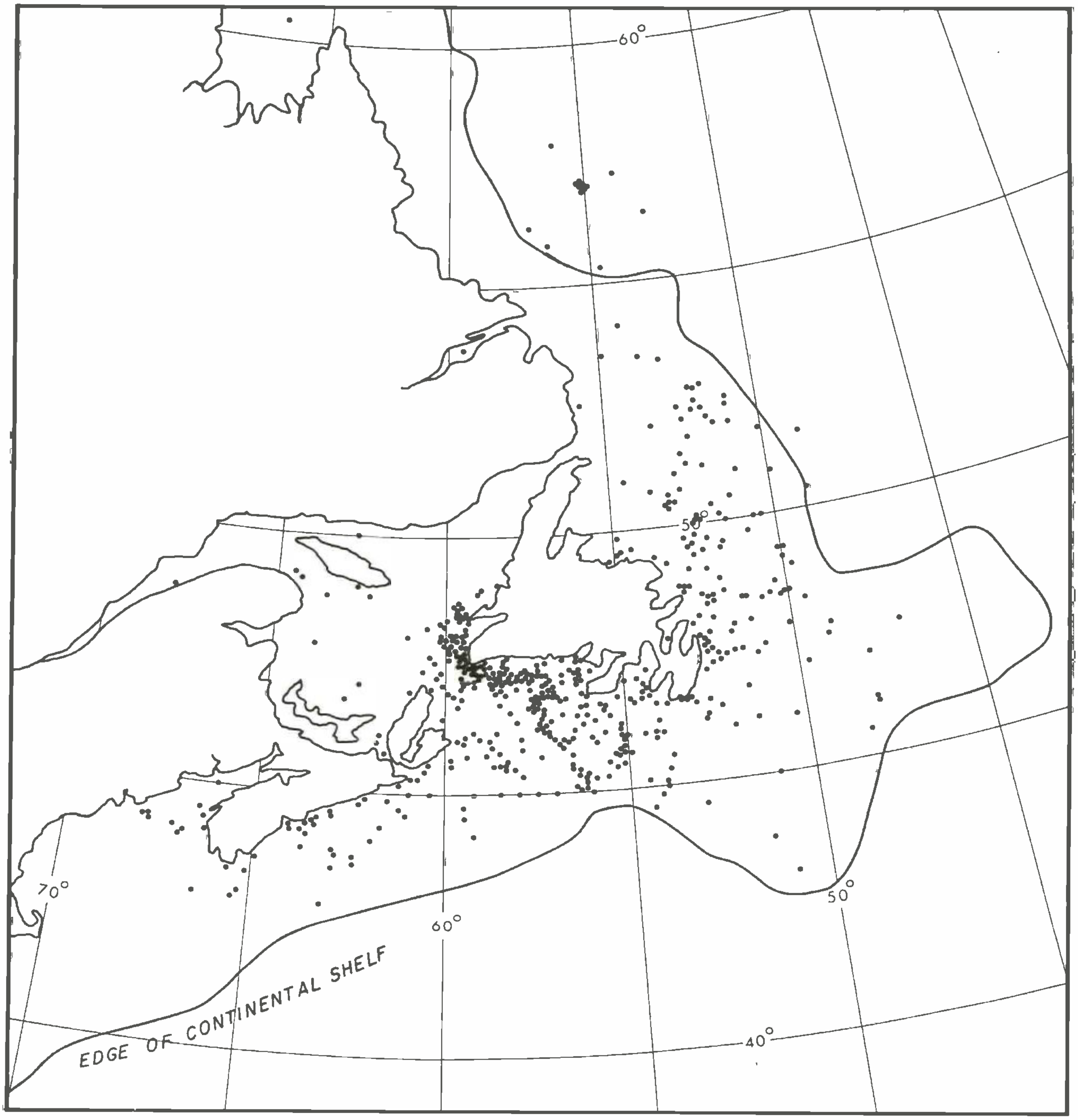


FIG. 21: LOCATIONS OF REPORTED SHIP ICING OFF EASTERN CANADA

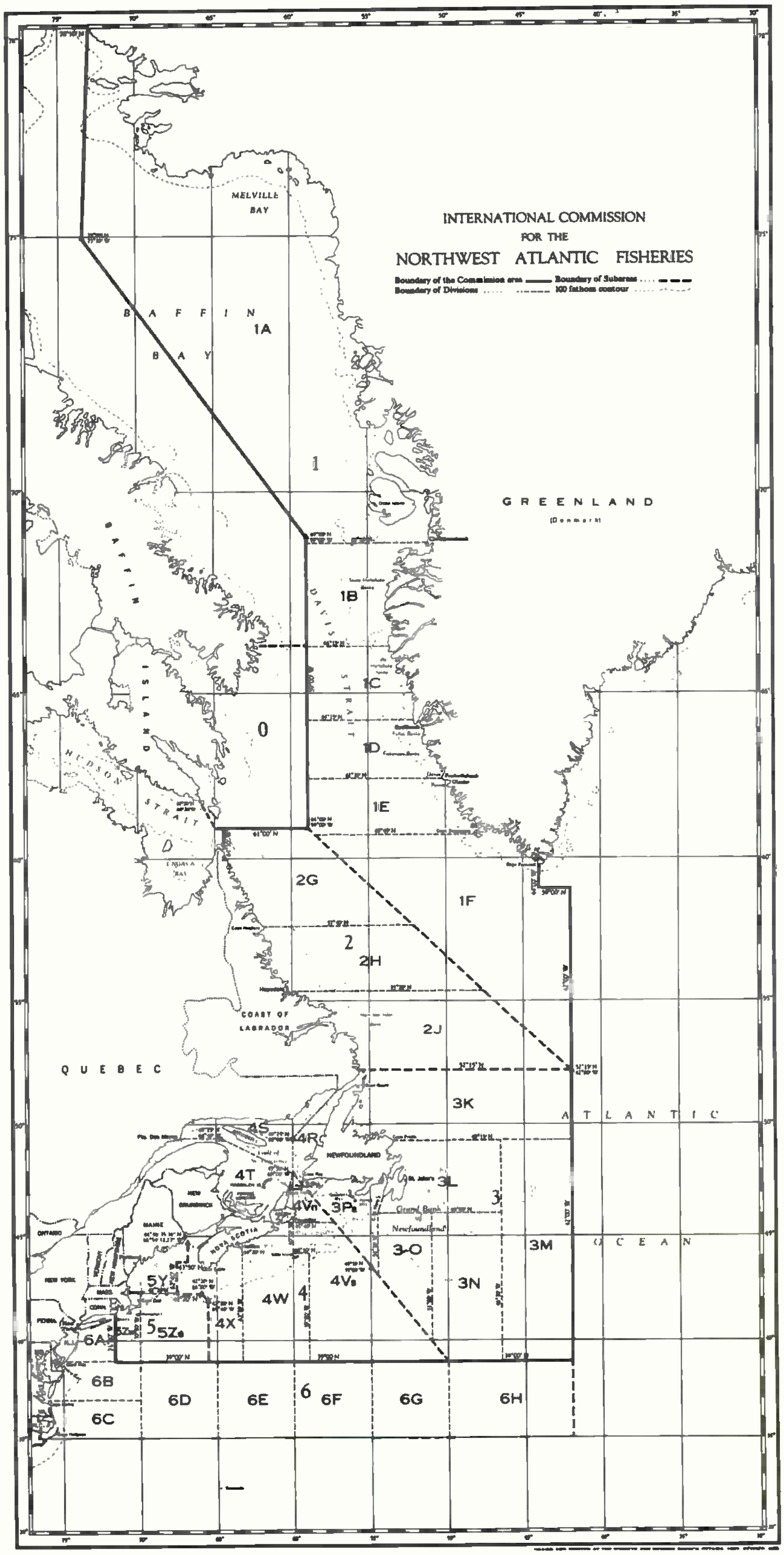


FIG. 22: DESIGNATED SEA AREAS OF THE INTERNATIONAL COMMISSION FOR THE NORTHWEST ATLANTIC FISHERIES (ICNAF)

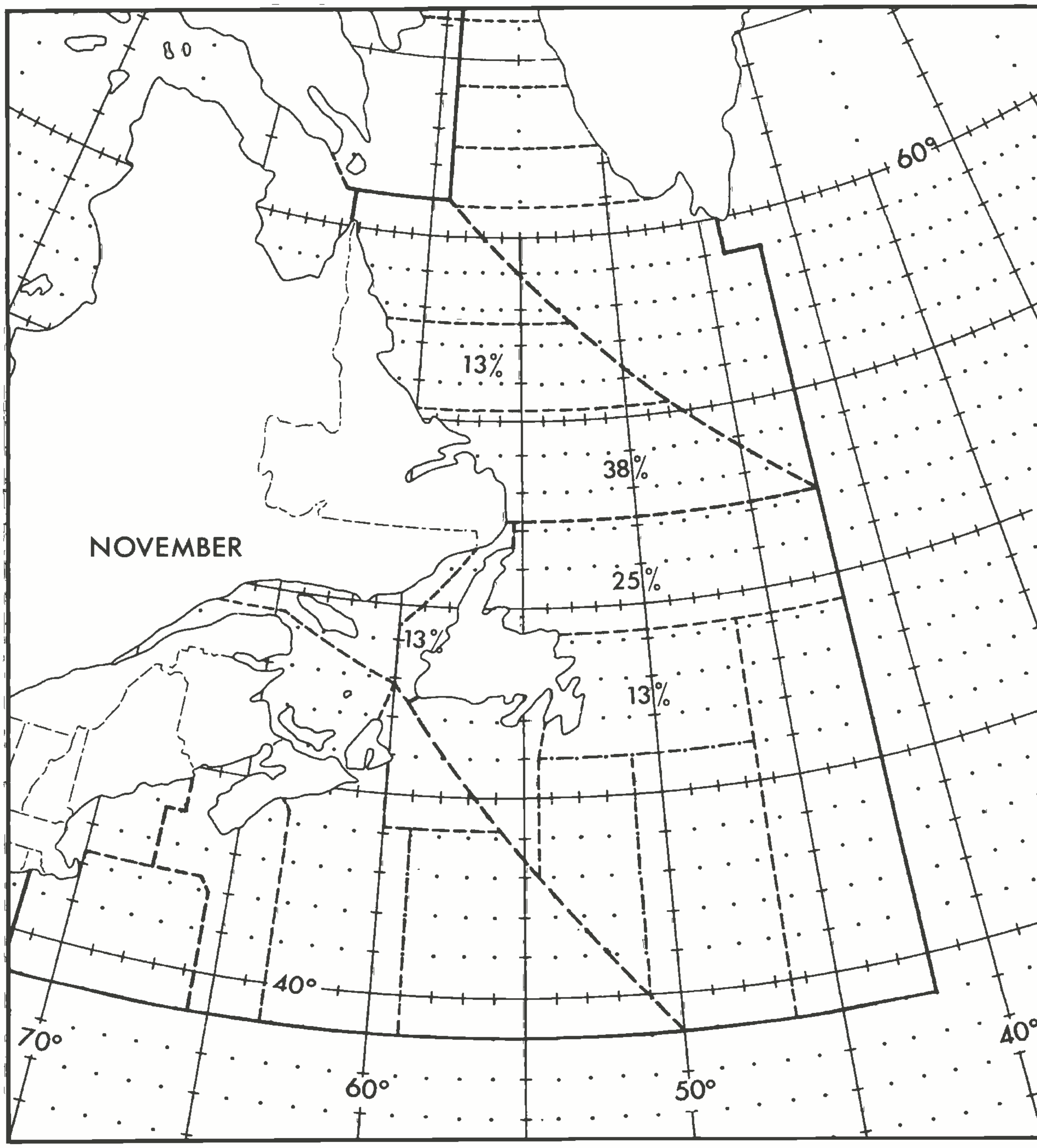


FIG. 23: PERCENTAGE OF YEARS FOR WHICH ICING OF SEVERITY GREATER THAN SLIGHT HAS BEEN REPORTED IN THE VARIOUS ICNAF DIVISIONS FOR THE MONTH OF NOVEMBER

NUMBER OF YEARS OF DATA: 8

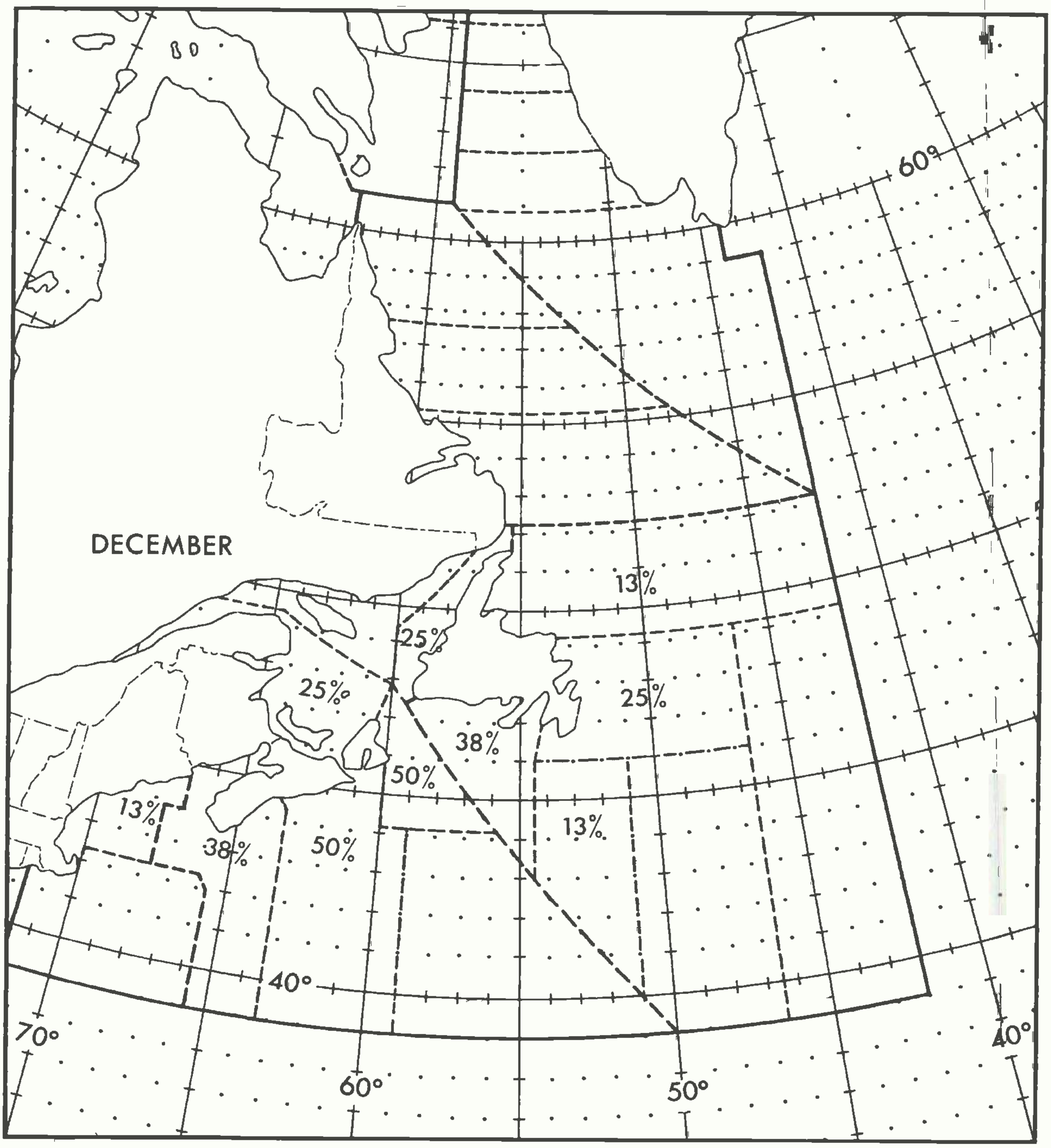


FIG. 24: PERCENTAGE OF YEARS FOR WHICH ICING OF SEVERITY GREATER THAN SLIGHT HAS BEEN REPORTED IN THE VARIOUS ICNAF DIVISIONS FOR THE MONTH OF DECEMBER

NUMBER OF YEARS OF DATA: 8

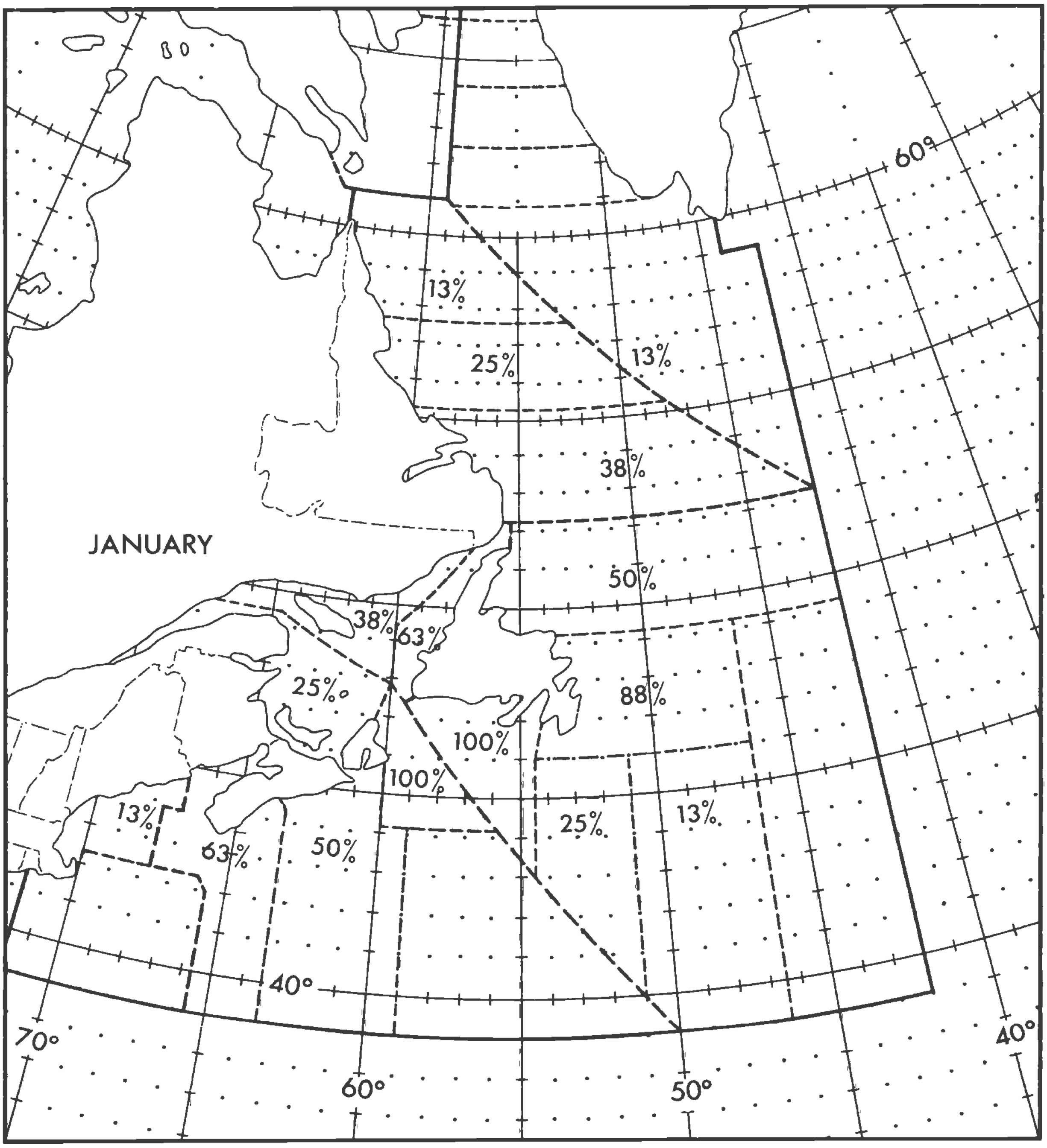


FIG. 25: PERCENTAGE OF YEARS FOR WHICH ICING OF SEVERITY GREATER THAN SLIGHT HAS BEEN REPORTED IN THE VARIOUS ICNAF DIVISIONS FOR THE MONTH OF JANUARY

NUMBER OF YEARS OF DATA: 8

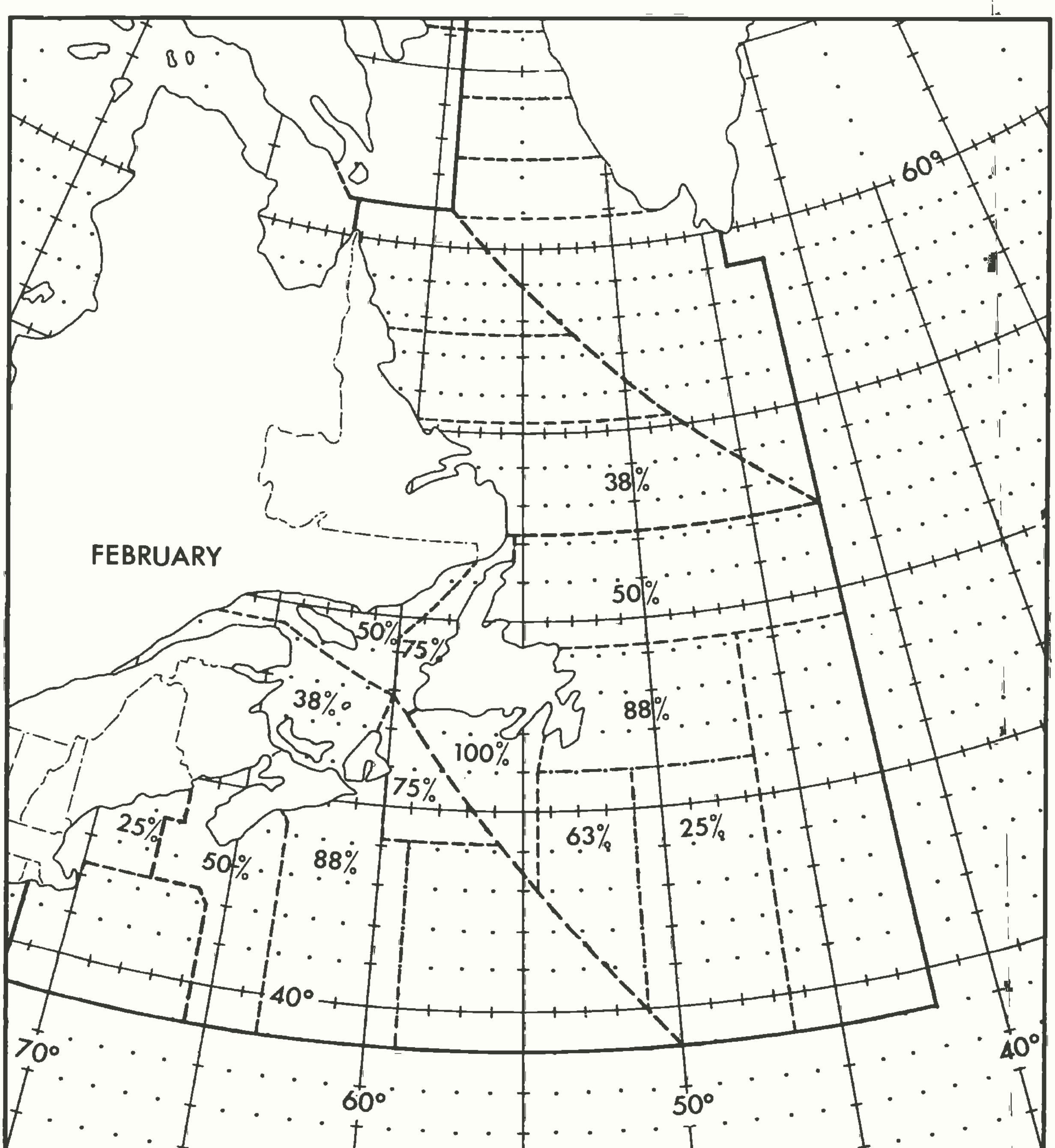


FIG. 26: PERCENTAGE OF YEARS FOR WHICH ICING OF SEVERITY GREATER THAN SLIGHT HAS BEEN REPORTED IN THE VARIOUS ICNAF DIVISIONS FOR THE MONTH OF FEBRUARY

NUMBER OF YEARS OF DATA: 8

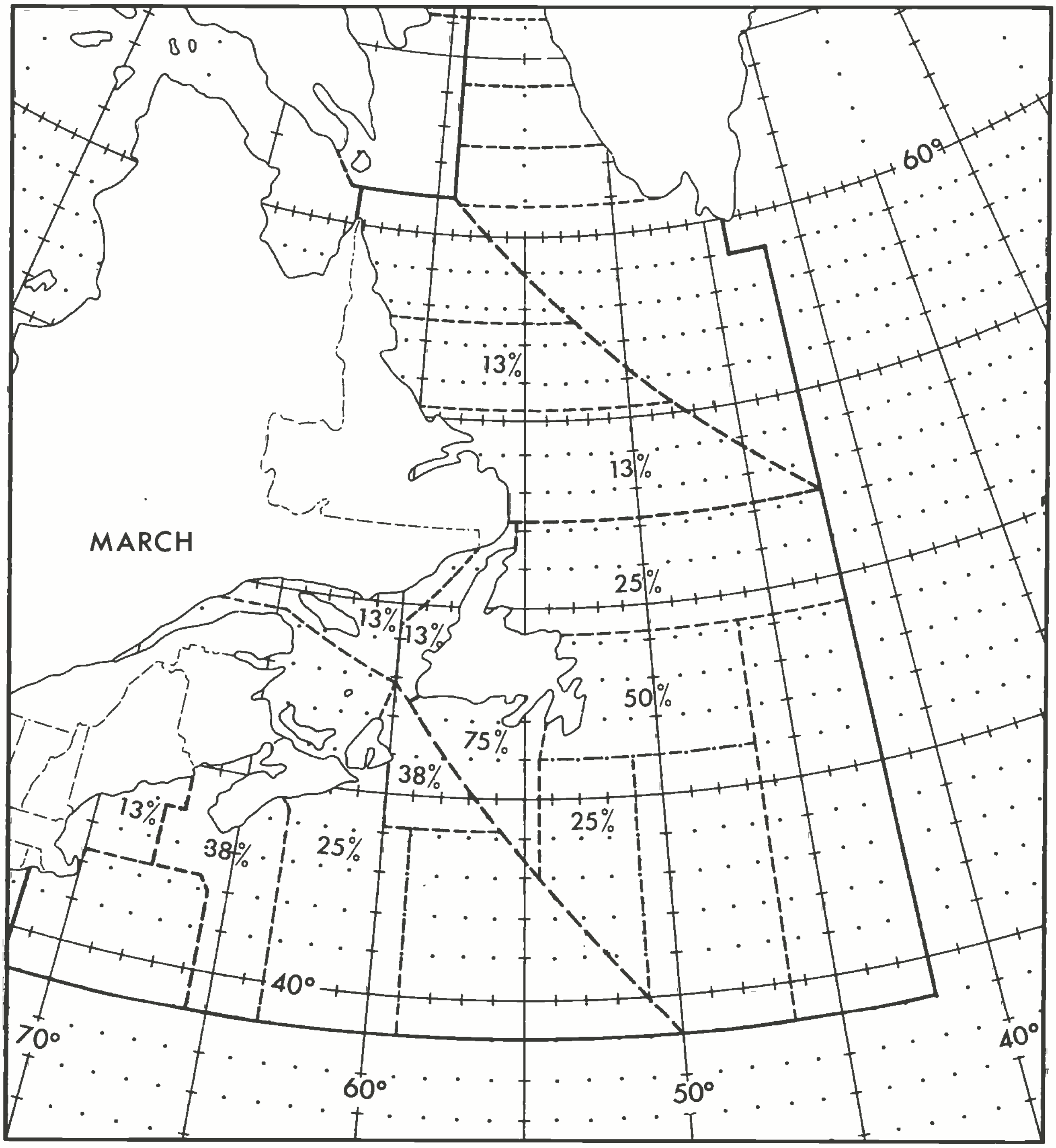


FIG. 27: PERCENTAGE OF YEARS FOR WHICH ICING OF SEVERITY GREATER THAN SLIGHT HAS BEEN REPORTED IN THE VARIOUS ICNAF DIVISIONS FOR THE MONTH OF MARCH

NUMBER OF YEARS OF DATA: 8

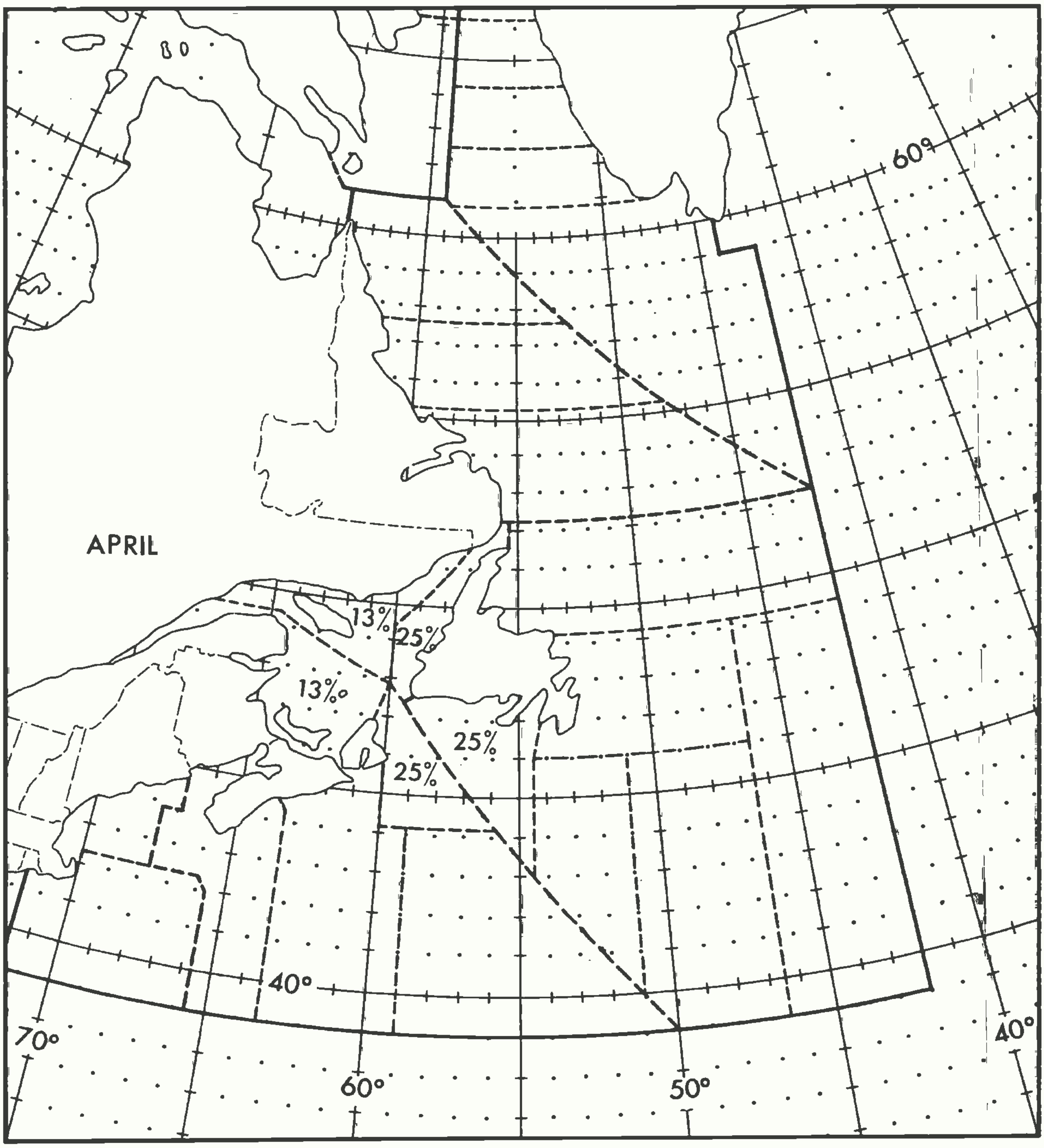
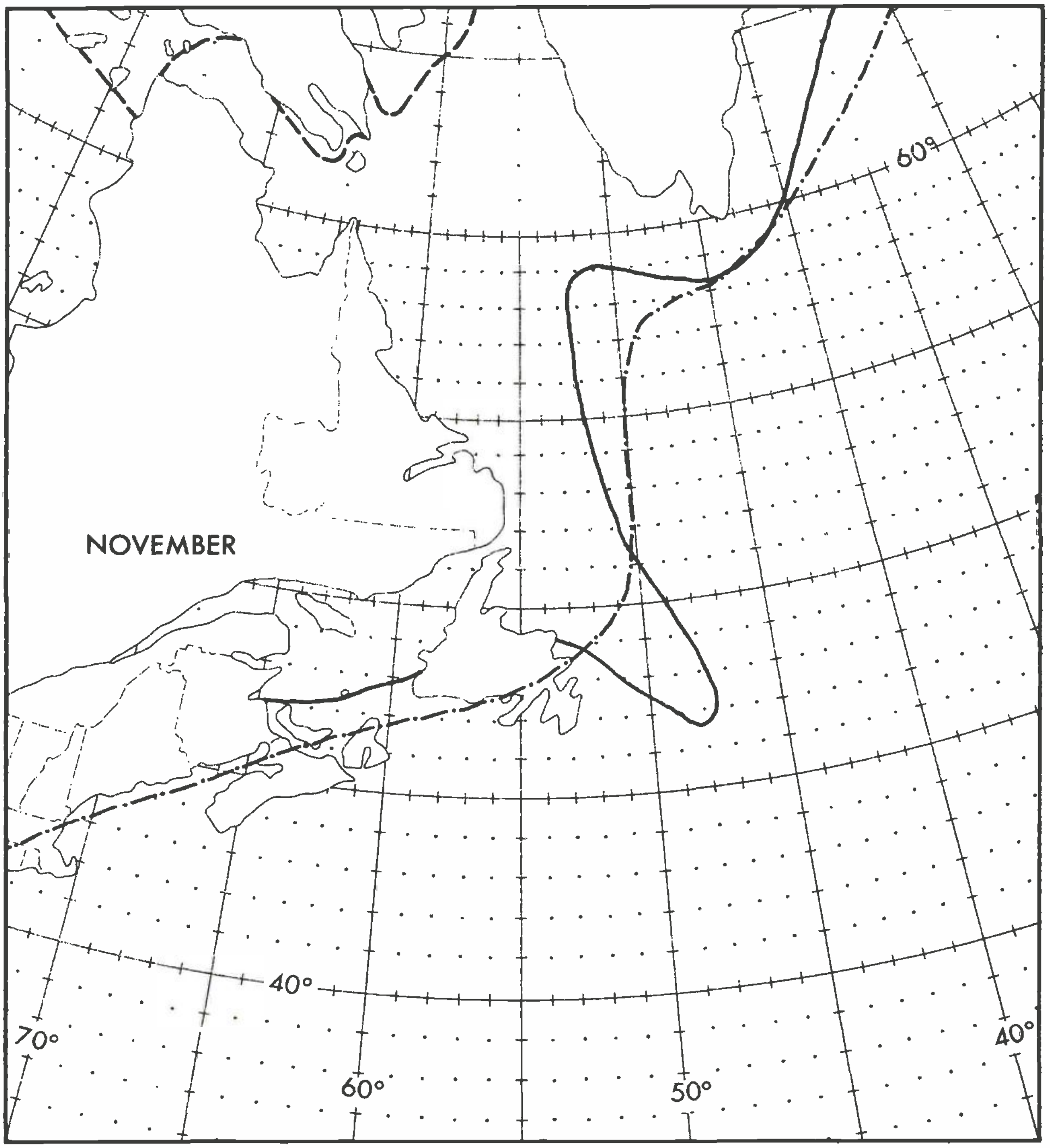


FIG. 28: PERCENTAGE OF YEARS FOR WHICH ICING OF SEVERITY GREATER THAN SLIGHT HAS BEEN REPORTED IN THE VARIOUS ICNAF DIVISIONS FOR THE MONTH OF APRIL

NUMBER OF YEARS OF DATA: 8

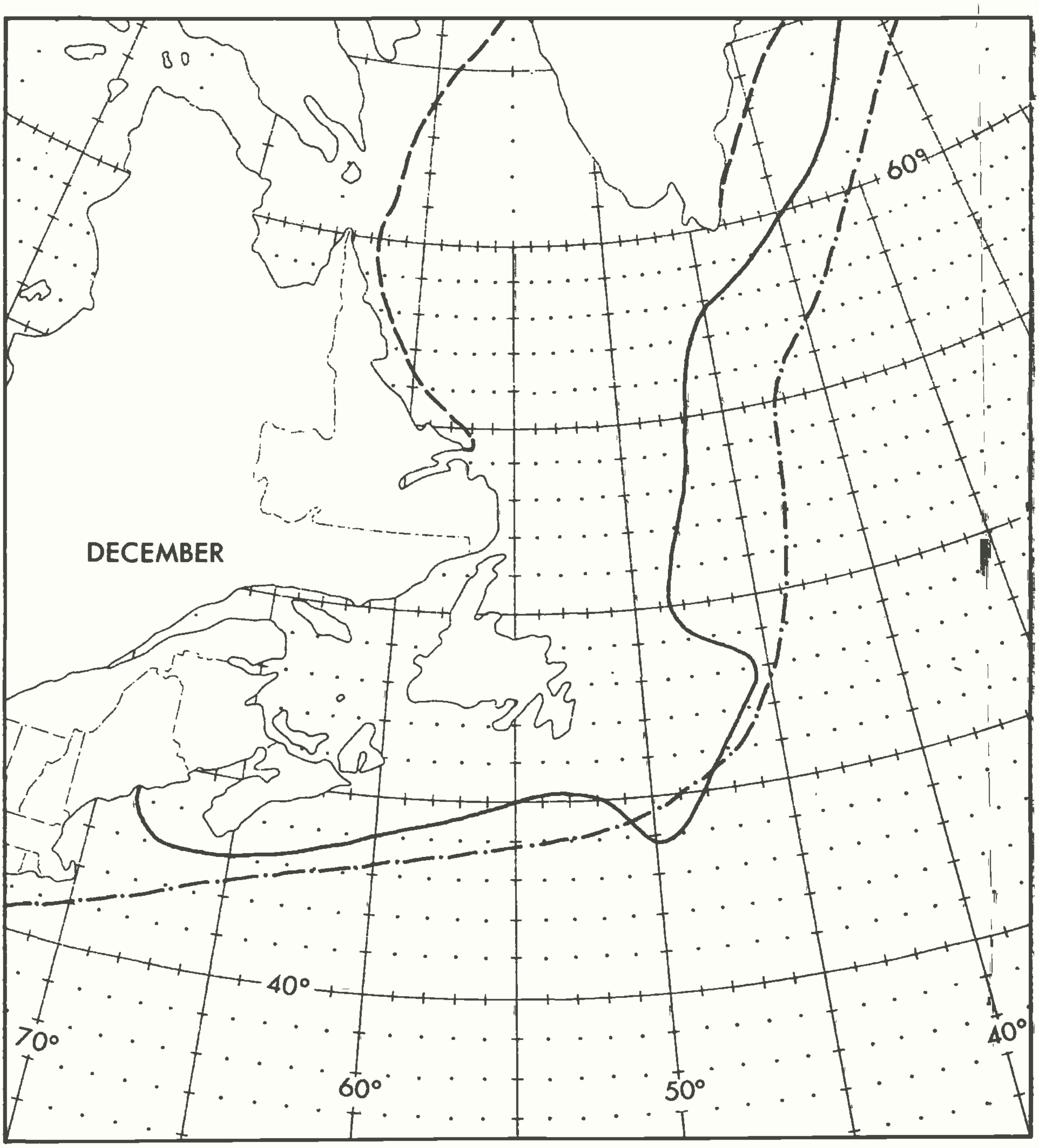


——— +4.4°C MEAN SEA SURFACE ISOTHERM

—·—·— 10% PROBABILITY OF AIR TEMPERATURE 0°C OR LESS

— — — APPROXIMATE MEAN ICE LIMIT

FIG. 29: MEAN SEA SURFACE TEMPERATURE OF 40°F (4.4°C) and 10% FREQUENCY OF OCCURRENCE OF SURFACE AIR TEMPERATURE OF 0°C OR LESS FOR THE MONTH OF NOVEMBER

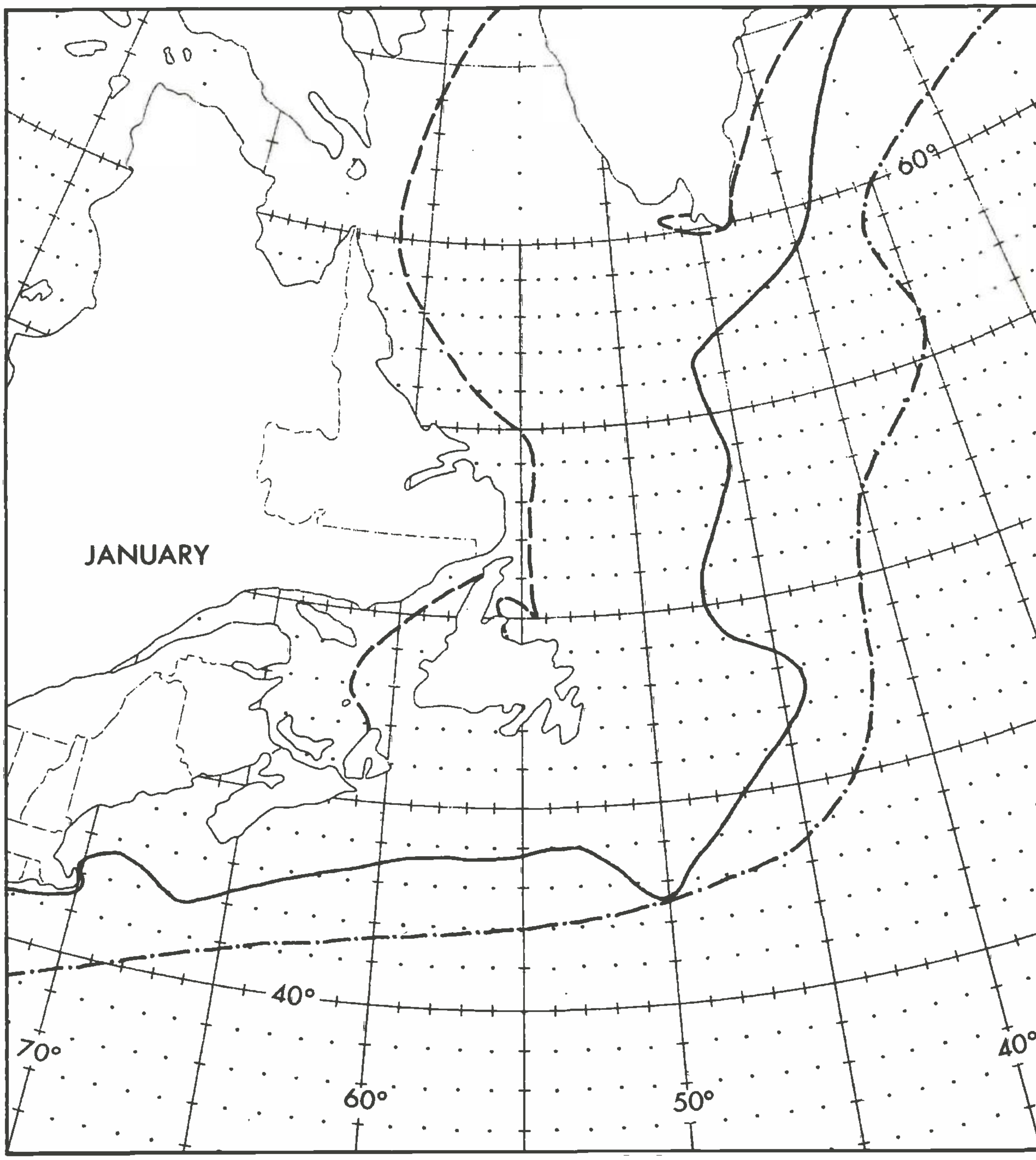


——— +4.4°C MEAN SEA SURFACE ISOTHERM

—·—·— 10% PROBABILITY OF AIR TEMPERATURE 0°C OR LESS

— — — APPROXIMATE MEAN ICE LIMIT

FIG. 30: MEAN SEA SURFACE TEMPERATURE OF 40°F (4.4°C) and 10% FREQUENCY OF OCCURRENCE OF SURFACE AIR TEMPERATURE OF 0°C OR LESS FOR THE MONTH OF DECEMBER

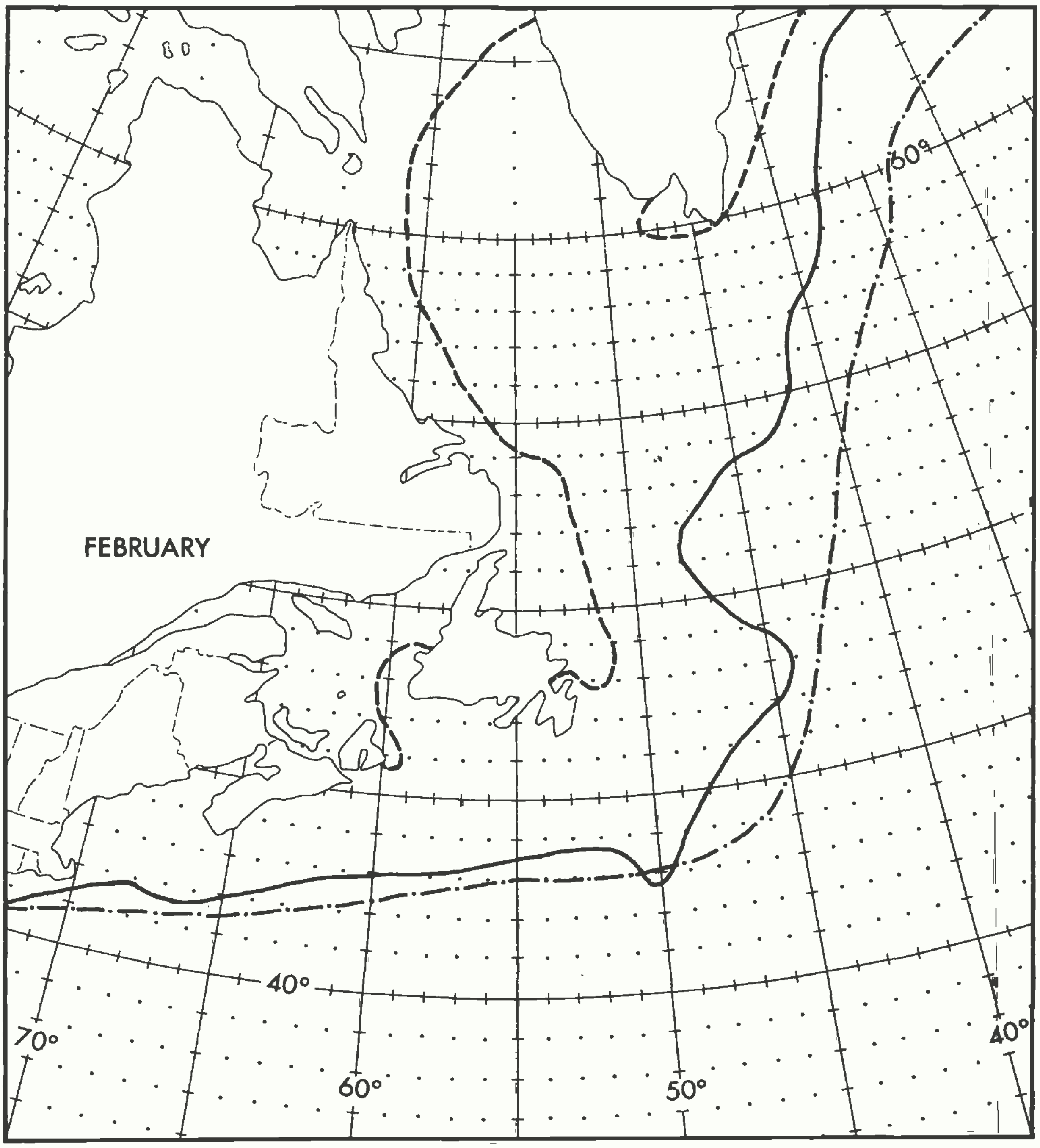


——— +4.4°C MEAN SEA SURFACE ISOTHERM

—·—·— 10% PROBABILITY OF AIR TEMPERATURE 0°C OR LESS

— — — APPROXIMATE MEAN ICE LIMIT

FIG. 31: MEAN SEA SURFACE TEMPERATURE OF 40°F (4.4°C) and 10% FREQUENCY OF OCCURRENCE OF SURFACE AIR TEMPERATURE OF 0°C OR LESS FOR THE MONTH OF JANUARY

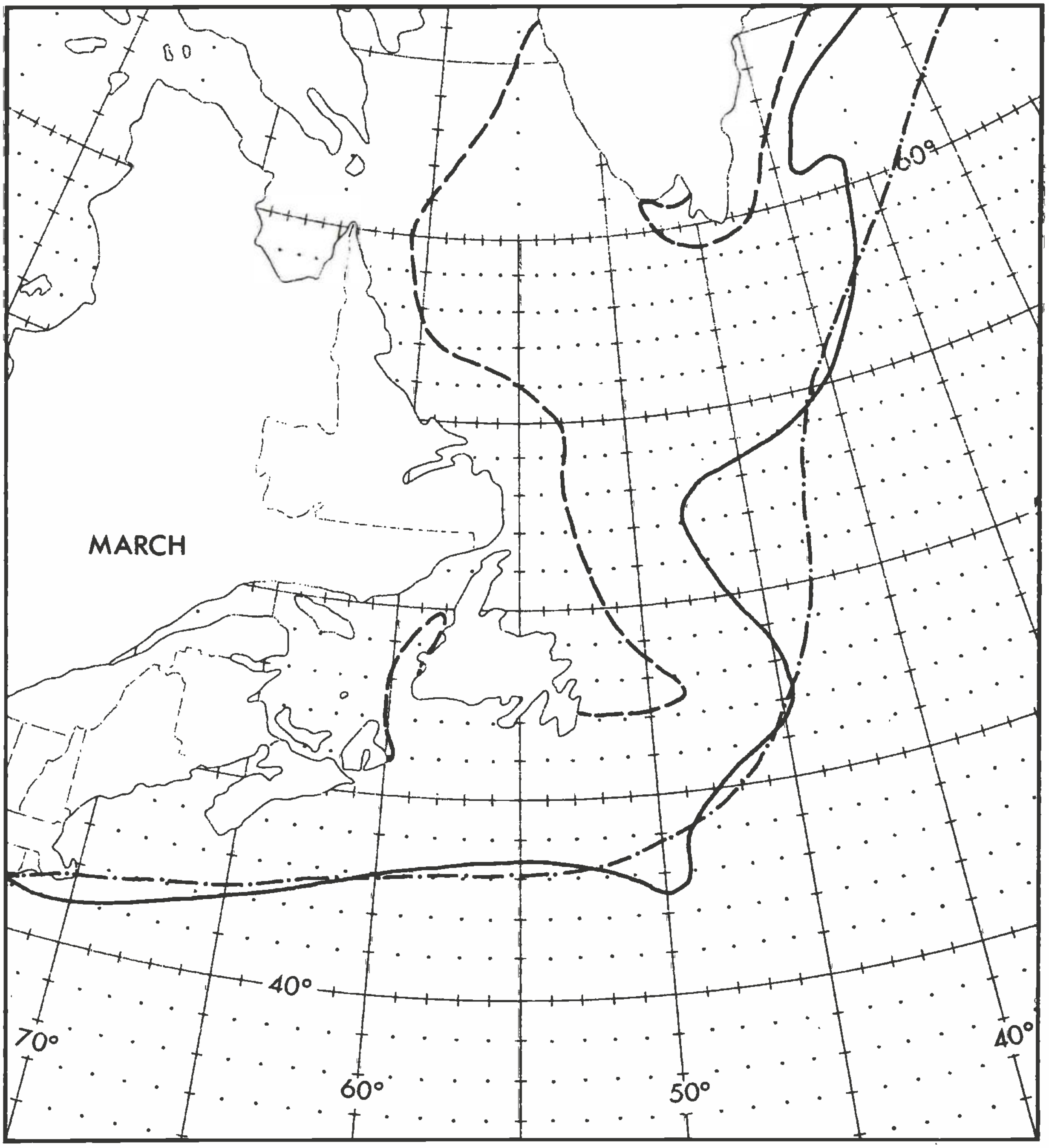


+4.4°C MEAN SEA SURFACE ISOTHERM

10% PROBABILITY OF AIR TEMPERATURE 0°C OR LESS

APPROXIMATE MEAN ICE LIMIT

FIG. 32: MEAN SEA SURFACE TEMPERATURE OF 40°F (4.4°C) and 10% FREQUENCY OF OCCURRENCE OF SURFACE AIR TEMPERATURE OF 0°C OR LESS FOR THE MONTH OF FEBRUARY

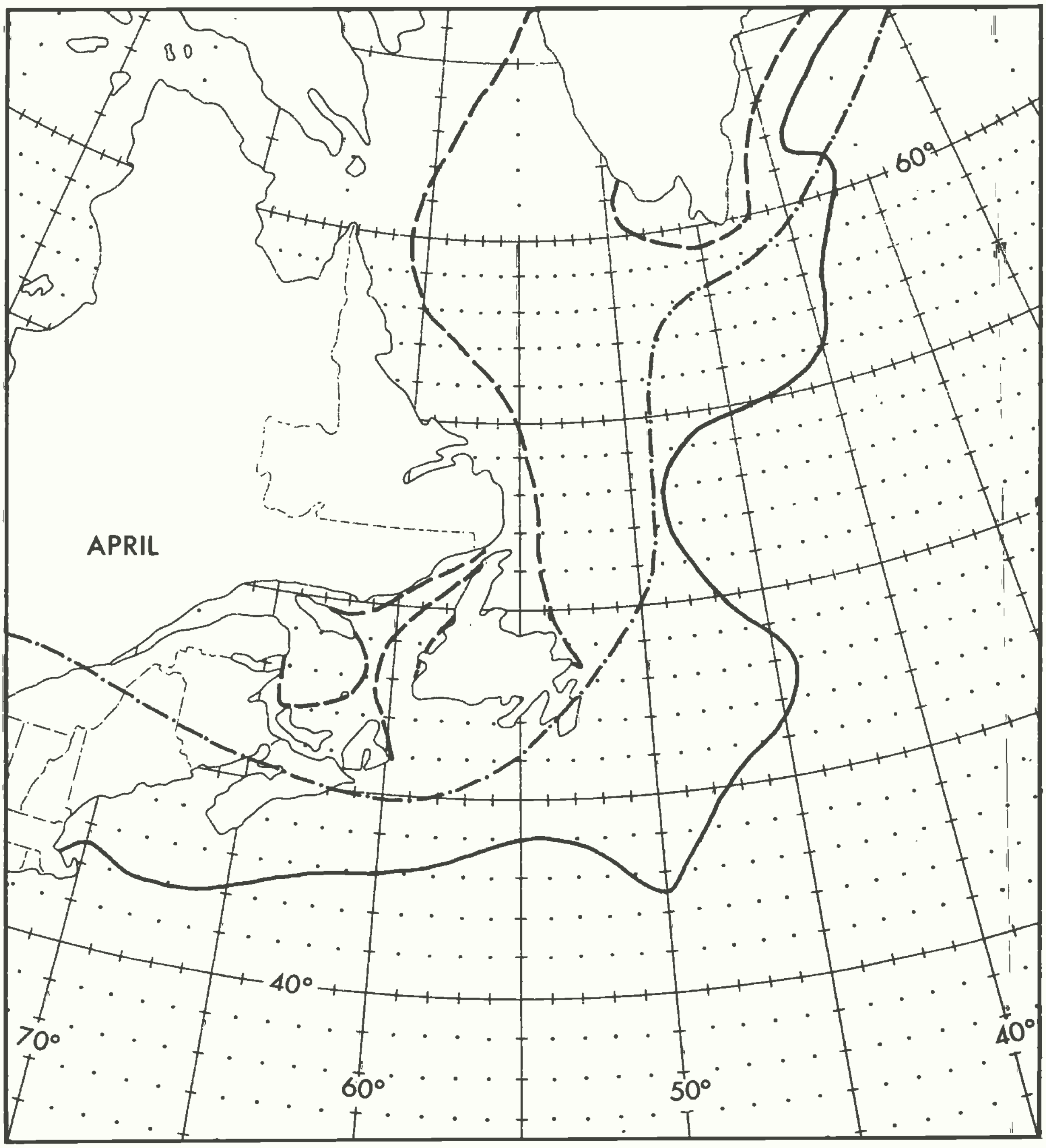


+4.4°C MEAN SEA SURFACE ISOTHERM

10% PROBABILITY OF AIR TEMPERATURE 0°C OR LESS

APPROXIMATE MEAN ICE LIMIT

FIG. 33: MEAN SEA SURFACE TEMPERATURE OF 40°F (4.4°C) and 10% FREQUENCY OF OCCURRENCE OF SURFACE AIR TEMPERATURE OF 0°C OR LESS FOR THE MONTH OF MARCH

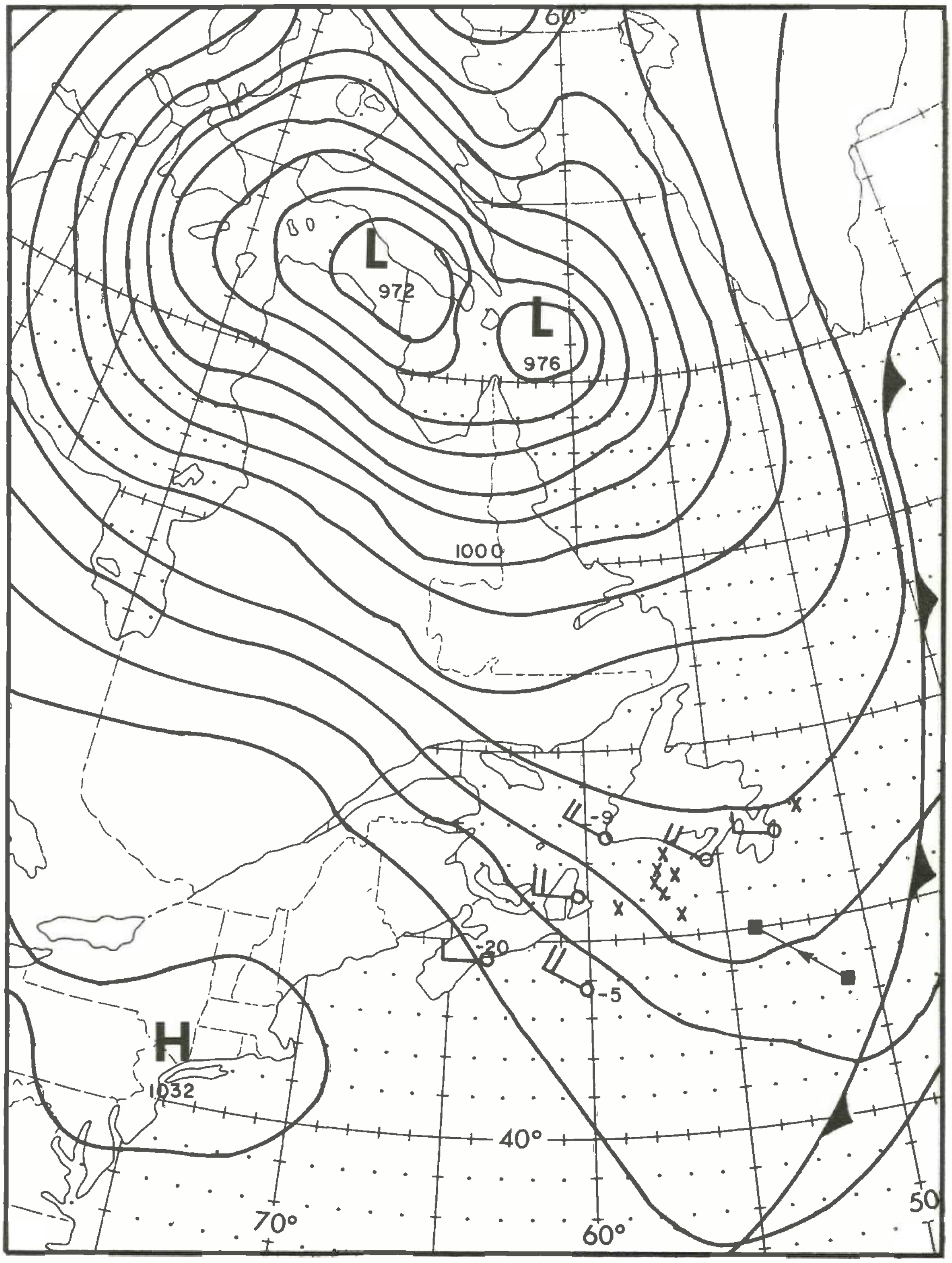


+4.4°C MEAN SEA SURFACE ISOTHERM

10% PROBABILITY OF AIR TEMPERATURE 0°C OR LESS

APPROXIMATE MEAN ICE LIMIT

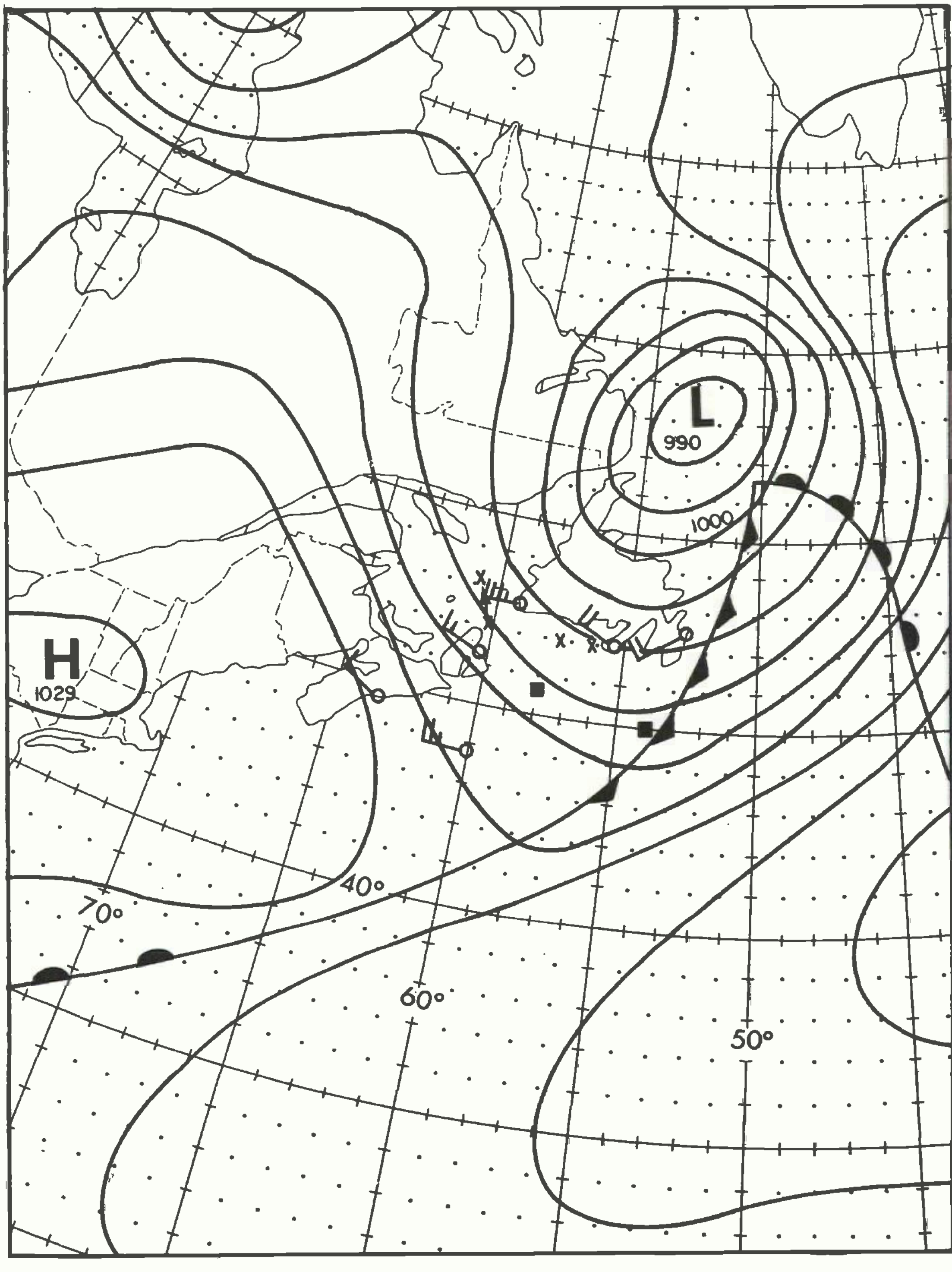
FIG. 34: MEAN SEA SURFACE TEMPERATURE OF 40°F (4.4°C) and 10% FREQUENCY OF OCCURRENCE OF SURFACE AIR TEMPERATURE OF 0°C OR LESS FOR THE MONTH OF APRIL



X – VESSELS EXPERIENCING ICING

■ – VESSEL NOT EXPERIENCING ICING

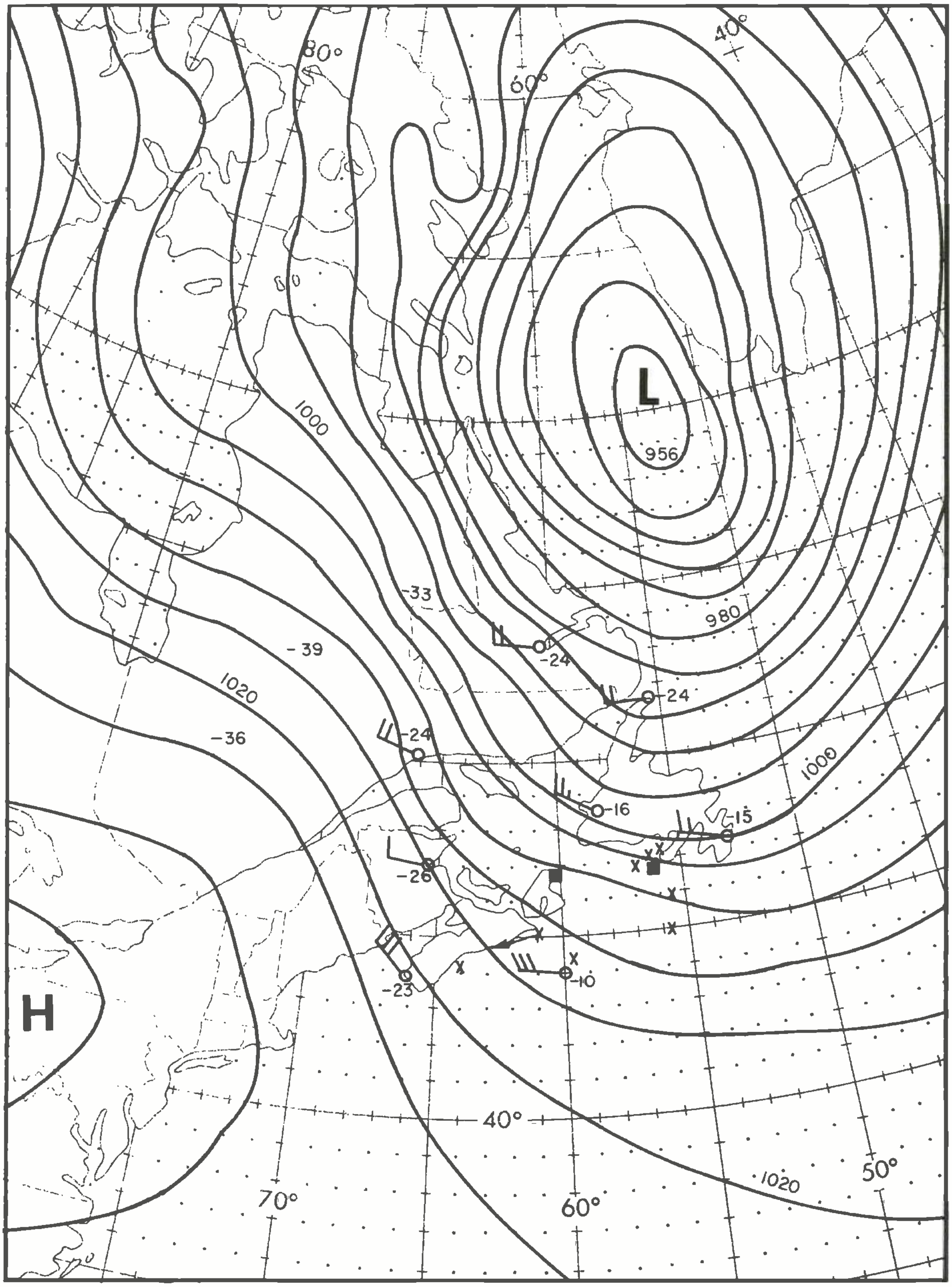
FIG. 35: SURFACE CHART SHOWING METEOROLOGICAL SYSTEM RESPONSIBLE FOR ICING OCCURRENCES ON 14 FEBRUARY, 1970



X – VESSELS EXPERIENCING ICING

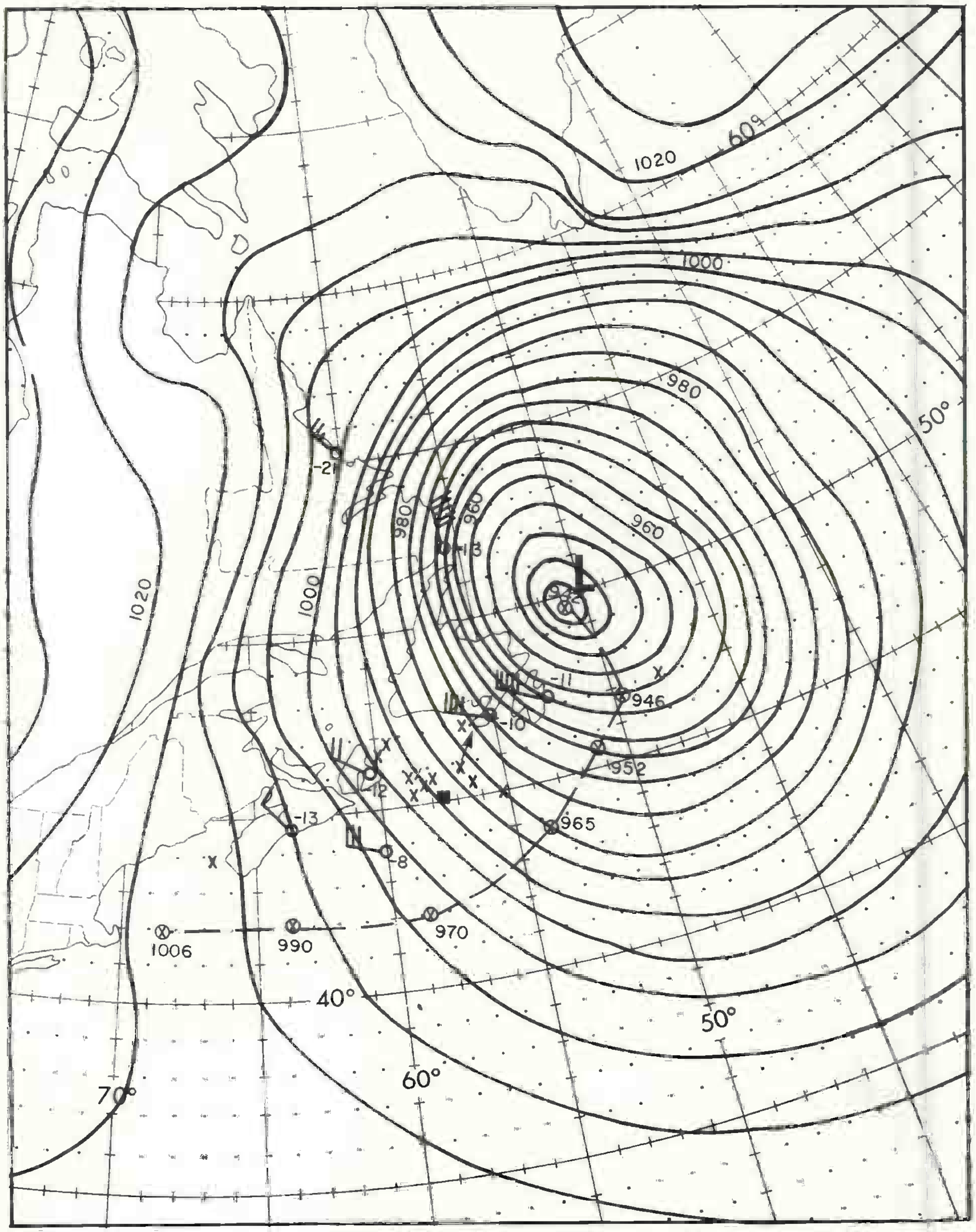
■ – VESSEL NOT EXPERIENCING ICING

FIG. 36: SURFACE CHART SHOWING METEOROLOGICAL SYSTEM RESPONSIBLE FOR ICING OCCURRENCES ON 17 FEBRUARY, 1970



X — VESSELS EXPERIENCING ICING
■ — VESSELS NOT EXPERIENCING ICING — SHELTERING IN LEE OF LAND

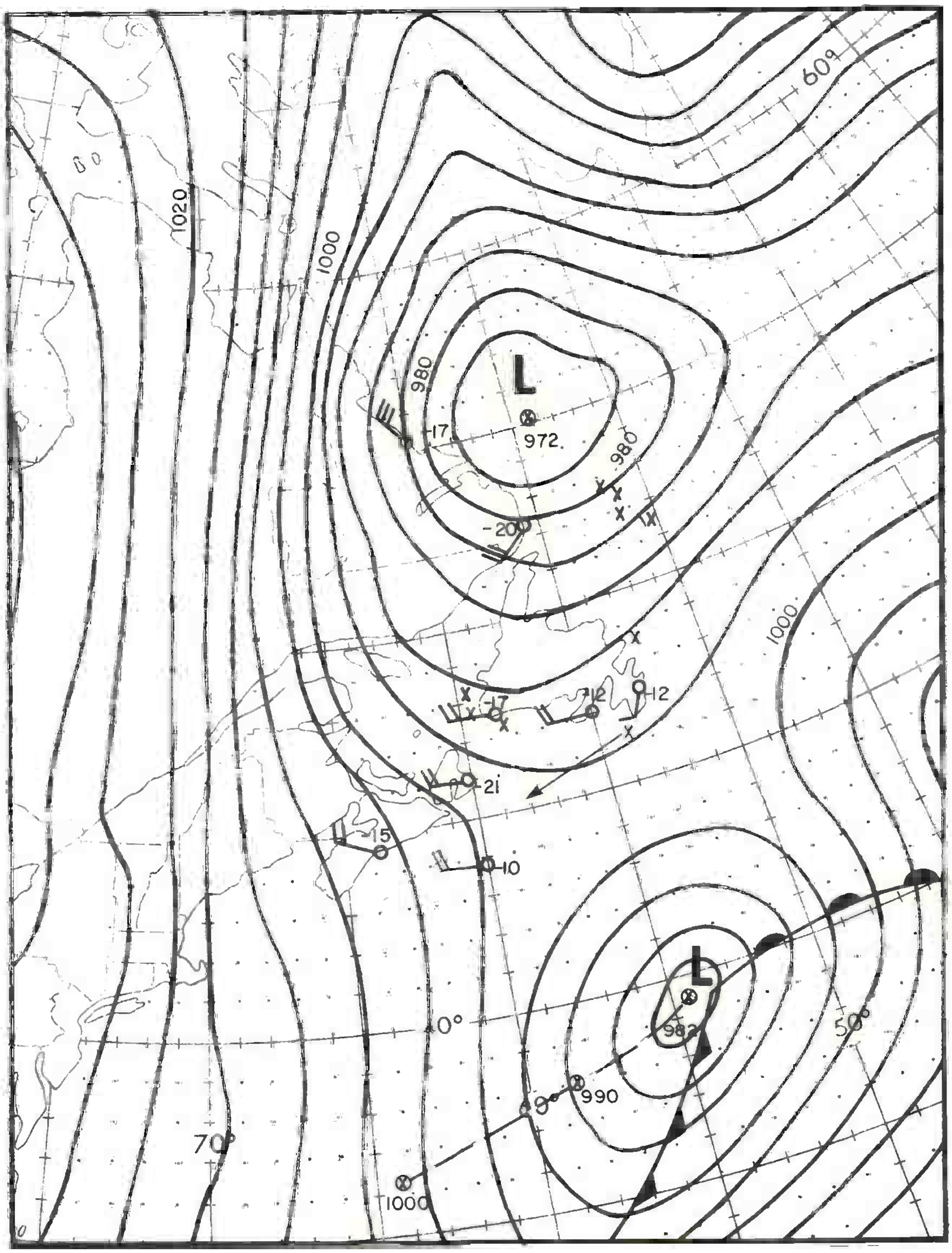
FIG. 37: SURFACE WEATHER CHART FOR 1200 GMT, 27 JANUARY, 1972



X – VESSELS EXPERIENCING ICING

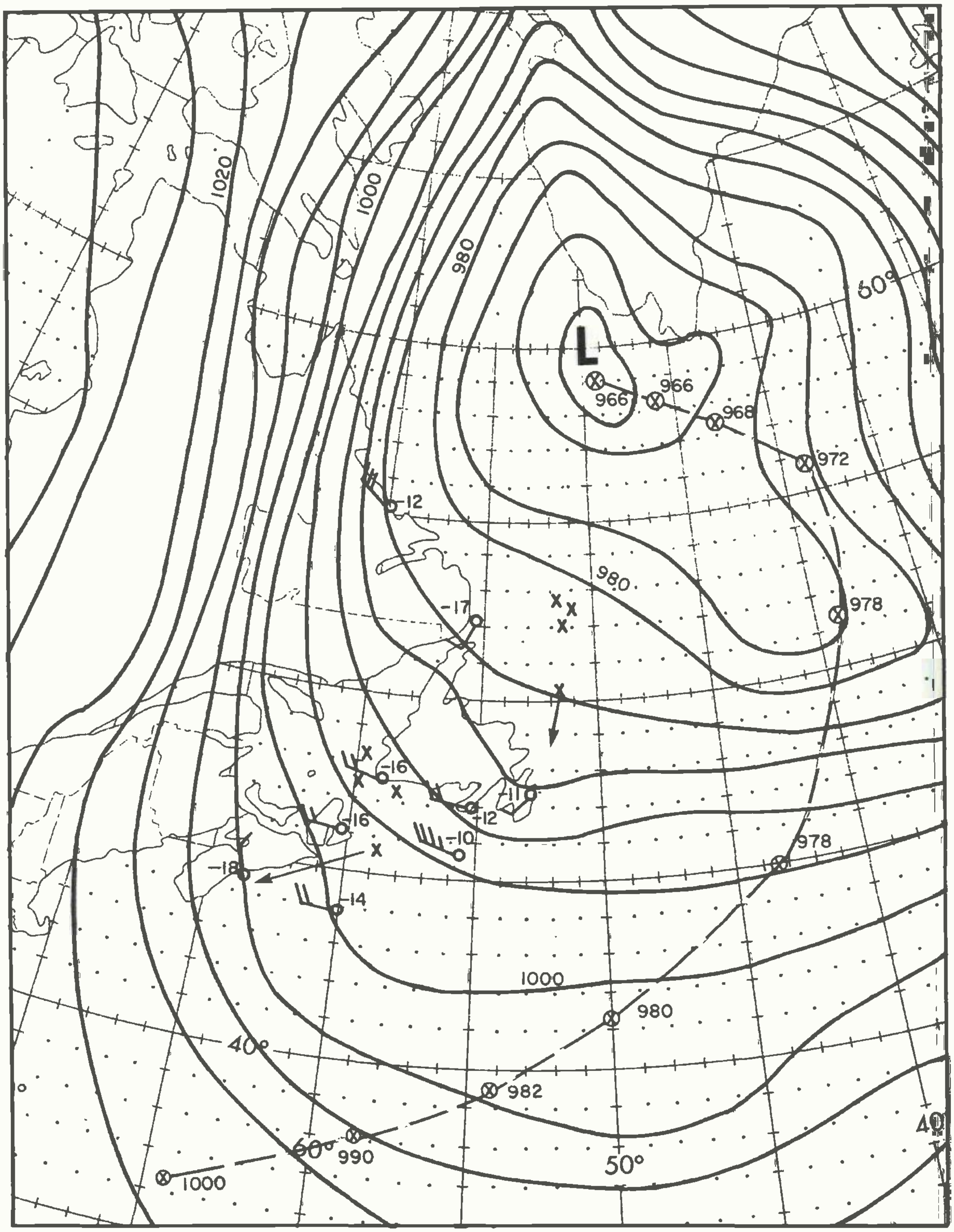
■ – VESSEL IN PACK ICE – NOT EXPERIENCING ICING

FIG. 38: SURFACE WEATHER CHART FOR 0600 GMT, 12 MARCH, 1974



X — VESSELS EXPERIENCING ICING

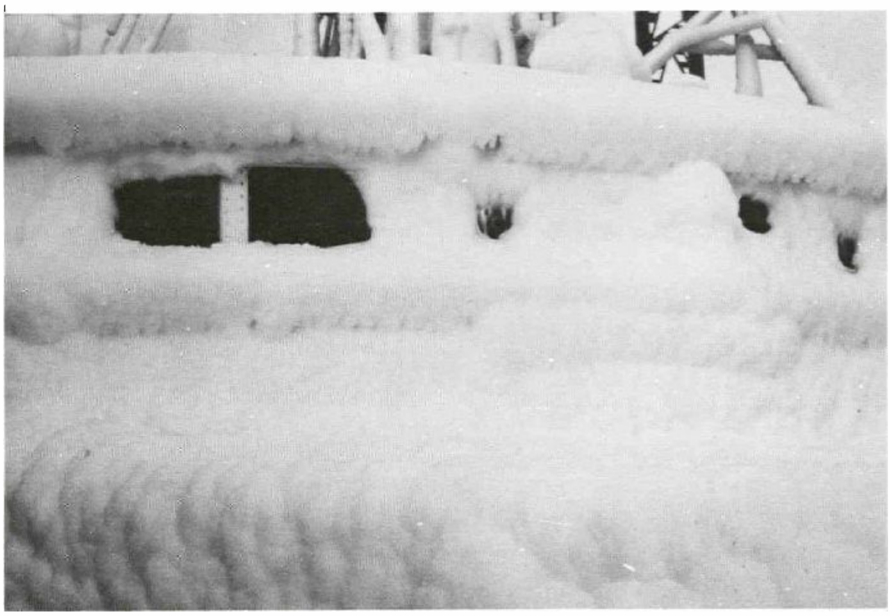
FIG. 39: SURFACE WEATHER CHART FOR 0000 GMT, 14 FEBRUARY, 1979



X – VESSELS EXPERIENCING ICING

FIG. 40: SURFACE WEATHER CHART FOR 1800 GMT, 15 FEBRUARY, 1979

(a) ICE BUILD-UP ON RAILS, ANCHOR AND FORESTAY



(b) ICE BUILD-UP ON WHEELHOUSE FRONT

FIG. 41: ICING OF STERN TRAWLER 26-27 JANUARY 1972

FIG. 42: ICE BUILD-UP ON GOVERNMENT SURVEY SHIP 5-9 FEBRUARY 1972

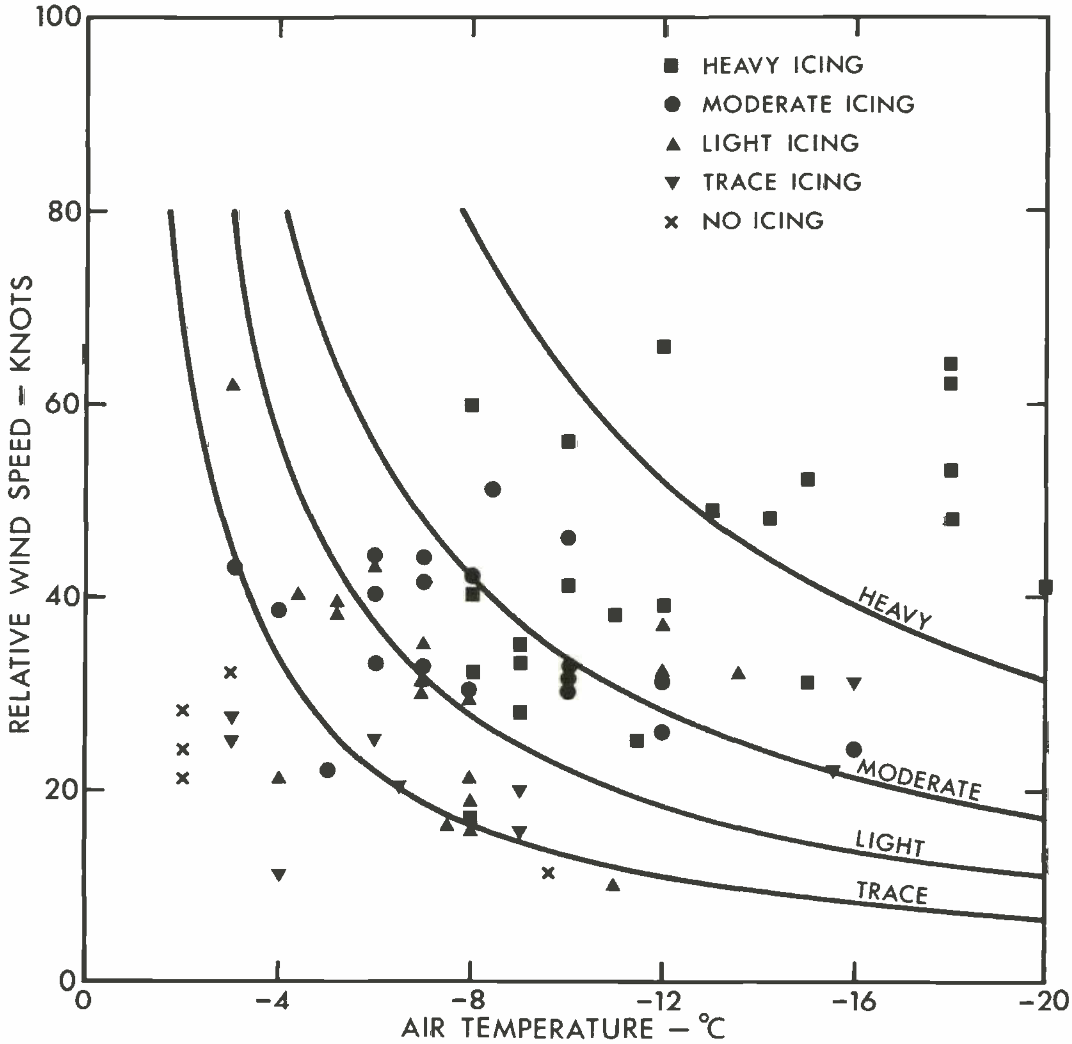


FIG. 43: EFFECT OF AIR TEMPERATURE AND RELATIVE WIND SPEED ON REPORTED ICING SEVERITY FOR FISHING VESSELS STEAMING AT 5 KNOTS OR GREATER

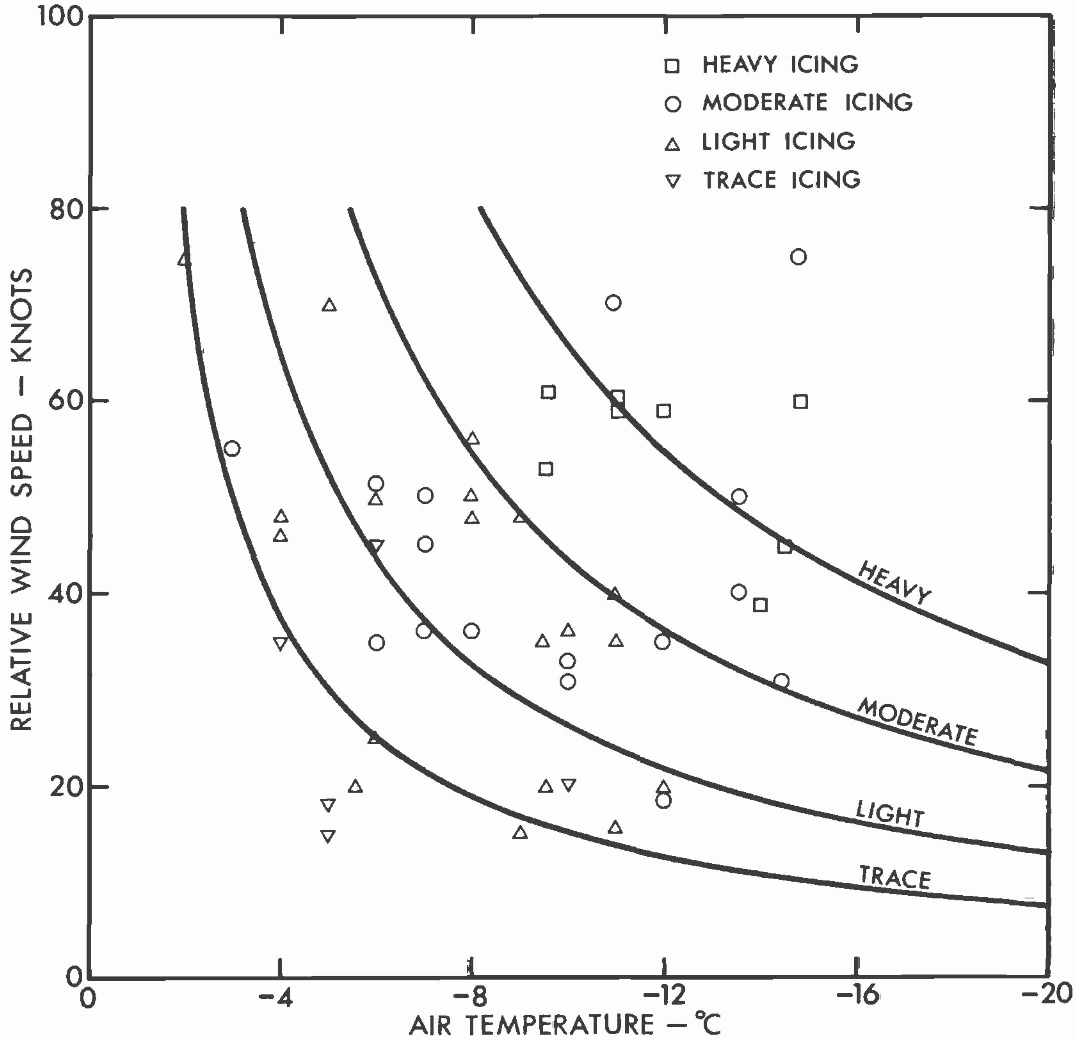
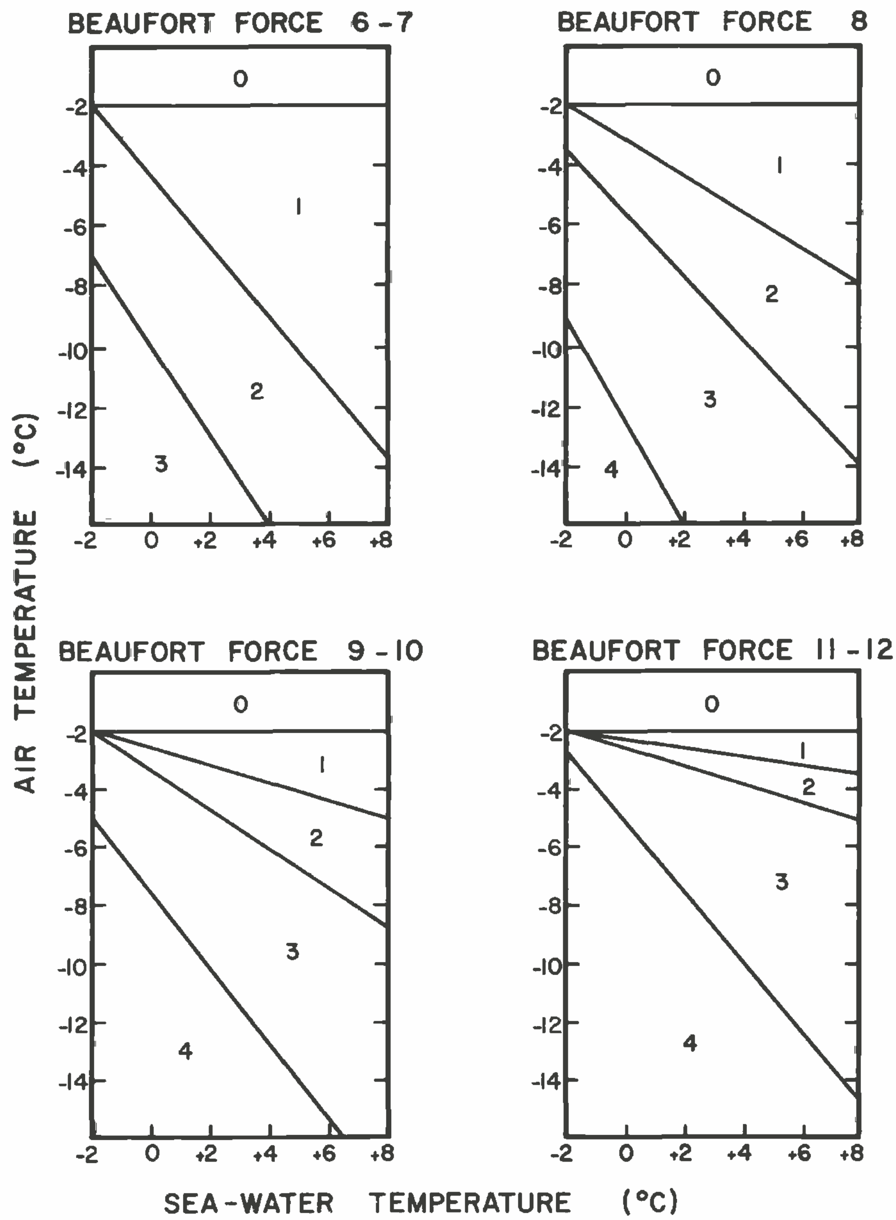
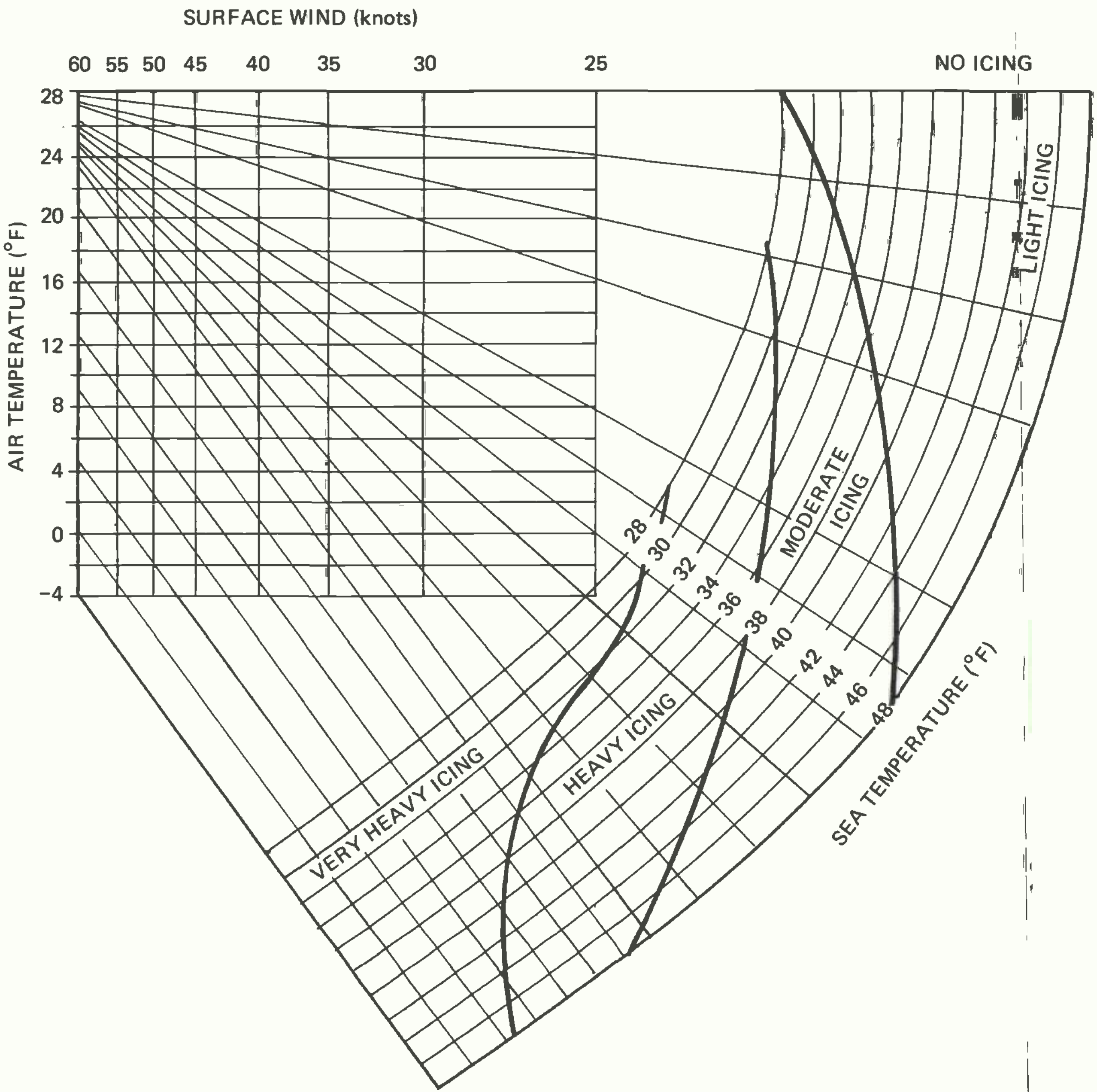


FIG. 44: EFFECT OF AIR TEMPERATURE AND RELATIVE WIND SPEED ON REPORTED ICING SEVERITY FOR FISHING VESSELS AT LOW SPEEDS (4 KNOTS AND BELOW)



DEGREE OF ICING:	0 —	NONE		
	1 —	LIGHT	=	1 - 3 CM / 24 HR
	2 —	MODERATE	=	4 - 6 CM / 24 HR
	3 —	SEVERE	=	7 - 14 CM / 24 HR
	4 —	VERY SEVERE	=	$\geqslant$ 15 CM / 24 HR

FIG. 45: MERTINS' CHARTS OF ICING ON FISHING VESSELS AT SLOW SPEEDS IN WINDS OF BEAUFORT FORCE 6 — 12
(REPRODUCED FROM REF. 45)



THE ICING CATEGORIES USED BY THE NWS ARE:

CATEGORY	ACCUMULATION
Light	0.4" to 1.4" in 24 hours
Moderate	1.4" to 2.6" in 24 hours
Heavy	2.6" to 5.7" in 24 hours
Very Heavy	5.7" + in 24 hours

FIG. 46: COMISKEY'S NOMOGRAPH FOR FORECASTING ICING CONDITIONS
(REPRODUCED FROM REF. 46)

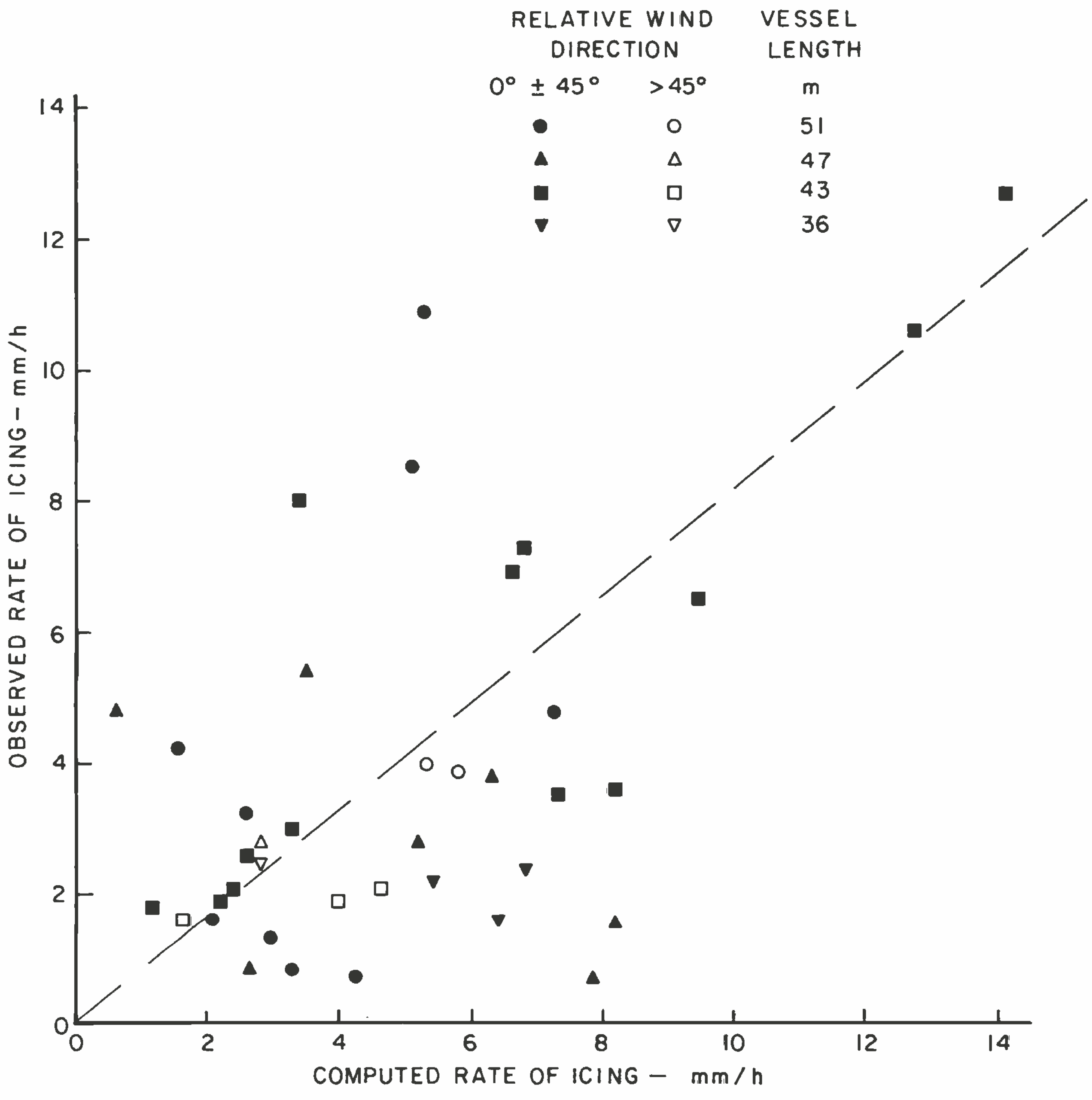


FIG. 47: COMPARISON BETWEEN CALCULATED RATE OF ICING AND THAT ESTIMATED FROM TRAWLER ICING REPORTS

BROKEN LINE REPRESENTS BEST LEAST SQUARES FIT THROUGH THE ORIGIN, SLOPE = 0.82

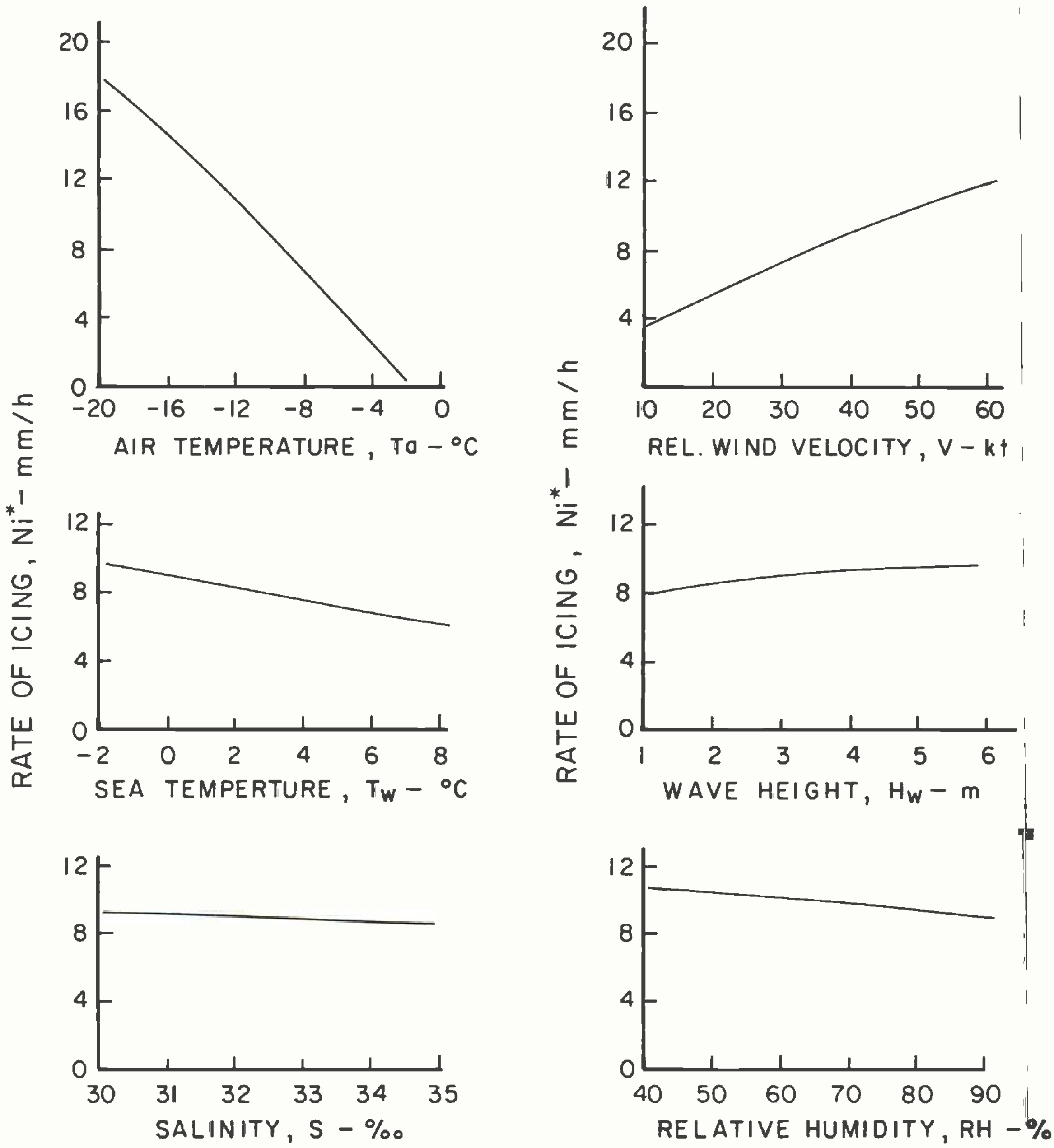


FIG. 48: EFFECT OF MAJOR VARIABLES ON THE RATE OF ICING

STANDARD CONDITIONS TAKEN AS: Ta = −10°C,
Tw = 0°C, V = 40 kt, Hw = 3m, S = 32‰, RH = 90%
EACH PARAMETER VARIED IN TURN

APPENDIX A

SIMPLIFIED FORMULAE FOR TOTAL COLLECTION EFFICIENCY OF CYLINDERS AND RECTANGULAR BODIES

In an attempt to simplify the calculation of the droplet collection efficiency of cylinders and rectangular bodies and to obviate the use of curves such as presented in References 14 and 49 the following formulae are proposed. These formulae have been derived for the rather limited range of atmospheric conditions appropriate to trawler icing and the icing of static structures.

The properties of air at -5°C and 100 kPa (750 mm Hg) have been used, and the deviations from these conditions that are to be expected in this context have negligible effect on the final result. Thus only the variables of velocity, droplet diameter, and cylinder diameter (or body width) are involved in the formulae and are combined into a single parameter, ζ (zeta), of the form:

$$\zeta = V^p \, d^q \, D^r \qquad \text{(A.1)}$$

where V = velocity
d = droplet diameter
D = cylinder diameter (or body width)

The indices p, q and r must be chosen such that the families of curves, resulting from the use of the K and ϕ (or Re_o) parameters as used in References 14 and 49 all collapse to a single curve when the collection efficiency, E_m, is plotted against ζ.

It was found that this requirement was satisfied over a representative range of values of V, d and D (with the exception of the simultaneous combination of very small values of all three parameters) by the following values of the indices:

$$p = 0.6$$

$$q = 1.6$$

$$r = -1$$

whence

$$\zeta = \frac{V^{0.6} \, d^{1.6}}{D} \qquad \text{(A.1a)}$$

The units used throughout in evaluation ζ are:

for V – m/s, for d – μm, and for D – m

To conform to the obvious requirements that when V or d is very large, or when D is very small (i.e. when $\zeta \rightarrow \infty$), the collection efficiency, E_m, approaches unity, and that $E_m = 0$ when $\zeta \rightarrow 0$, a relationship between ζ and E_m of the following form was adopted:

$$E_m = \frac{1}{1 + \dfrac{\alpha}{(\zeta - \beta)^n}} \quad \text{for } \zeta \geqslant \beta$$

$$E_m = 0 \qquad \text{for } \zeta < \beta \tag{A.2}$$

where α, β and n are constants.

Cylinder Collection Efficiency

Evaluation of α, β and n for the cylinder collection efficiency data presented in Reference 14 leads to the following relations:

$$E_m = \frac{1}{1 + \dfrac{3200}{\zeta - 3200}} = \frac{\zeta - 3200}{\zeta + 27000}, \quad \zeta \geqslant 3200$$

$$E_m = 0 \qquad \zeta < 3200 \tag{A.3}$$

This curve is presented in Figure A.1, together with actual values of E_m evaluated using Reference 14 over the following range of values:

V from 3 m/s to 60 m/s

d from 20 μm to 1000 μm

D from 0.03 m to 1 m

As the points indicate, the values of E_m are collapsed well by Equation (A.1a) onto a single curve, with the exception of a few points which lie below the curve, particularly at its lower end, and which correspond to combinations of the lower values of the parameters V, d and D.

The curve given by Equation (A.3) is seen to correspond to better than 0.04 in E_m value to the main group of points, while the extraneous points lie no more than 0.08 in E_m value from the curve.

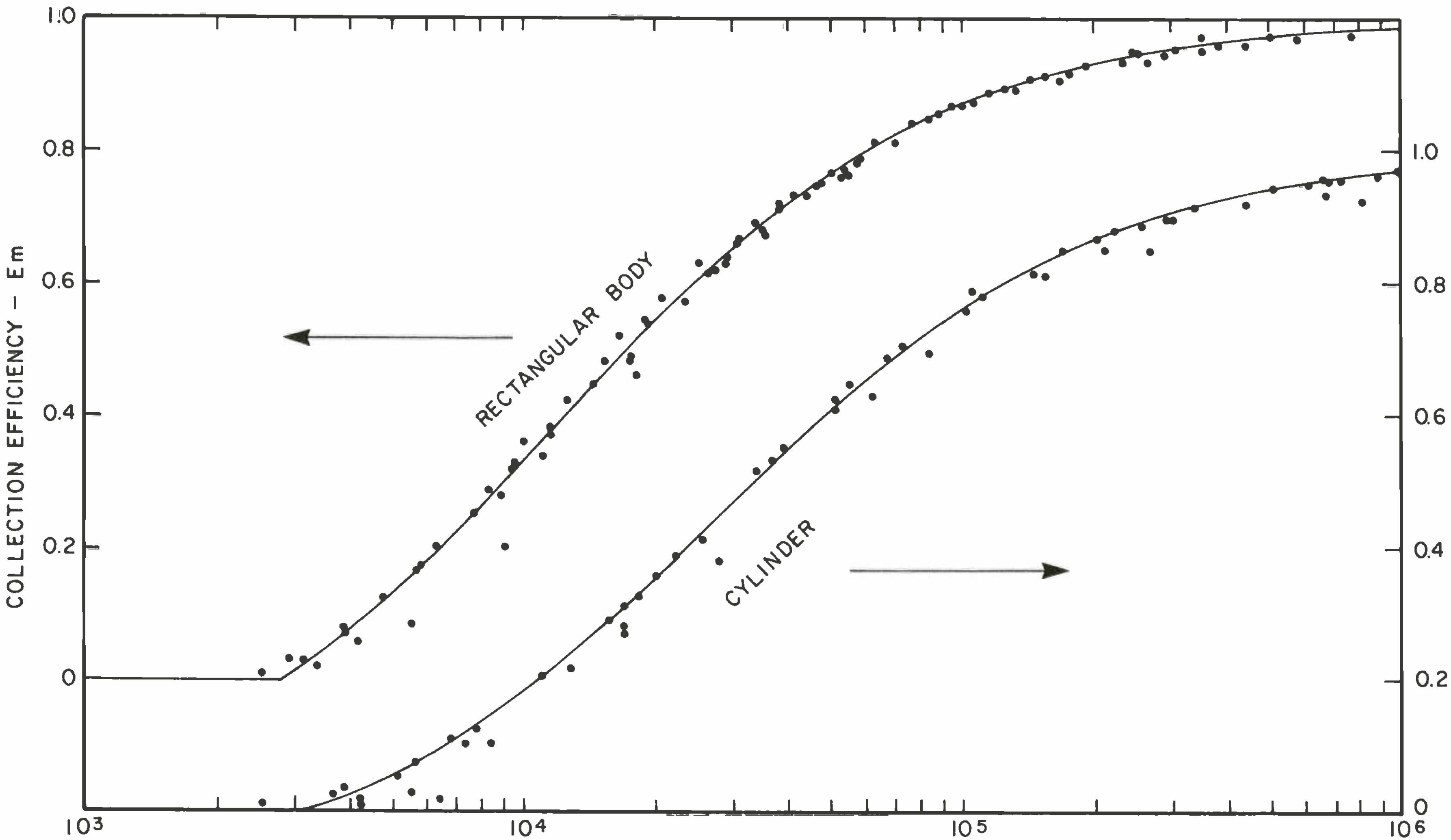
Rectangular Body Collection Efficiency

The rectangular body collection efficiency data of Reference 49 were used, and led to the following relations:

$$E_m = \frac{1}{1 + \dfrac{14500}{\zeta - 2800}} = \frac{\zeta - 2800}{\zeta + 11700}, \quad \zeta \geqslant 2800$$

$$E_m = 0 \qquad \zeta < 2800 \tag{A.4}$$

Figure A.1 presents this curve together with values of E_m evaluated using Reference 49 over the same range of the variables V and d as for the cylinder data; however the body width (D) was extended to 3m. The E_m data collapses onto a single curve rather better than for the cylinder case, except when the droplet Reynolds Number (Re_o) is less than about 20, in which case the points fall below the main grouping of points. The curve (Eq. (A.4)) agrees well with the main body of points.



$$\zeta = \frac{V^{0.6}\ d^{1.6}}{D}$$

FIG. A.1: COLLECTION EFFICIENCY OF CYLINDER AND RECTANGULAR BODY AS A FUNCTION OF PARAMETER ζ

APPENDIX B

DERIVATION OF EXPRESSION FOR PREDICTING THE ICING RATE OF FISHING TRAWLERS

B.1.0 HEAT BALANCE AT THE ICING SURFACE

Taking only the primary heat transfer processes acting at the icing surface into consideration, and assuming that the ice formation is a continuous steady-state process, an equilibrium heat balance at the icing surface may be formulated as follows:

$$q_f + q_w + q_c + q_e + q_a = 0 \qquad \text{(B.1)}$$

where q_f = latent heat of freezing a certain fraction of the impinging water,

q_w = heating (or cooling) of the impinging water to the equilibrium surface temperature,

q_c = heat transfer by convection to the surrounding air,

q_e = heat transfer by evaporation to the surrounding air,

q_a = heat conducted to or from the icing surface through the underlying structure.

Each of these terms will initially be considered individually in the following sub-sections.

B.1.1 The Latent Heat Term, q_f

The rate of water impingement on unit area of a surface may be expressed as:

$$R_w = EwV \qquad \text{(B.2)}$$

where E is the collection efficiency,

w is the liquid water content of the air,

V is the velocity of the air relative to the object or surface.

The collection efficiency expresses the degree to which the water drops in the air impinge on an object in their path, and are not deflected by the airflow around the object. The collection efficiency increases with relative velocity, and with drop size, and decreases with the size of the object on which the drops impinge. Because the size of the water drops involved in ship icing due to sea spray is large (>1 mm), they will be deflected little and the collection efficiency will be assumed to be 100%.

The distribution of drop sizes in the spray is unknown and varies with wind speed, ship speed, type and size of vessel, the location on the vessel, and with height above the sea surface. Data quoted by Borisenkov (Ref. 3) suggests the drop diameter varies from 1.0 to 3.5 mm (the average is 2.4 mm) as a result of spraying from swell waves. However, in the bow of the ship the water will be encountered in the form of "gushes" or "cascades" for which the concept of drop size seems inappropriate; nevertheless, for the want of a better concept, it will be employed in this analysis.

The liquid water content of the spray cloud is equally difficult to quantify in any unique way; however, Kachurin (Ref. 47) suggests that wave height is the chief factor governing this parameter. As with drop size, it may be assumed that the water content is also a function of the size, lines and speed of the vessel, and also a function of height above the sea surface. Kachurin proposes that for sailing speeds of 6-8 knots and headings of $0 \pm 40°$, a proportional relationship be assumed:

$$w = 10^{-3} H_w \ \text{kg/m}^3 \tag{B.3}$$

where H_w is the wave height in metres.

However, in the icing model developed here, it was found that a liquid water content one sixth of that given by expression (B.3) resulted in a significant improvement in correlation with observed results. As a result, the expression for liquid water content

$$w = 1.7 \times 10^{-4} H_w \ \text{kg/m}^3 \tag{B.3a}$$

has been adopted.

If a fraction, n, of the impinging water freezes on the surface, then the rate of ice growth per unit area is:

$$R_i = nR_w = nEwV \tag{B.4}$$

and if ℓ_f is the latent heat of freezing, then the heat released is:

$$q_f = \ell_f R_i \tag{B.5}$$

A.1.2 The Sensible Heat Term, q_w

If the equilibrium temperature, t_s, of the icing surface on which the water drops impinge is assumed to be the equilibrium freezing temperature, t_f, of water of the appropriate salinity (i.e. ignoring any temperature gradient across any water film on the icing surface), and the drop temperature immediately prior to impingement is t_d, then the heat given to the impinging water is:

$$q_w = R_w c_w (t_d - t_s) \tag{B.6}$$

where c_w is the specific heat of the impinging water $\simeq$ 4000 J/kgC

for s = 35‰ @ −10°C.

It should not be overlooked however that some of the impinging water will likely splash or run off the icing surface before reaching the equilibrium temperature, t_s. Thus a splash factor, s, should appropriately be introduced into Equation (B.6) as follows:

$$q_w = (1-s) R_w c_w (t_d - t_s) \tag{B.6a}$$

However, there seems little way of knowing the magnitude of the factor, s, but Kachurin (Ref. 47) suggests that about 0.75 of the water film runs off without freezing and assumes there is no contribution whatever to the heat balance from this water. In fact, it is likely that the temperature of the water film is close to that of the ice surface, and that it is only the water that splashes and is blown away at the moment of impingement that takes no part in the thermal process.

Because of these uncertainties the form of Equation (B.6) will be employed in the following analysis.

The temperature of the impinging water drops, t_d, is a function of many variables including the sea-surface temperature, the air temperature, the drop size and the time of flight.

An expression for the drop temperature may be derived by following the procedure due to Hardy (Ref. 50).

The rate of change of temperature of the drop due to convection is:

$$\left.\frac{dt}{d\tau}\right/_{conv} = Nu \frac{6\,k_a}{\rho_w c_w d^2} (t_a - t) \qquad \text{(B.7)}$$

where t = instantaneous drop temperature
t_a = air temperature
τ = time
Nu = Nusselt No.
k_a = thermal conductivity of air
ρ_w = density of water
c_w = specific heat of water
d = drop diameter

The rate of evaporation is given by:

$$\frac{dm}{d\tau} = Nu\pi dD\rho_a \frac{M_w}{M_a}\left(\frac{e_a - e}{p}\right) \qquad \text{(B.8)}$$

where m = mass
D = diffusivity of water vapour in air
ρ_a = density of air
M_w/M_a = ratio of molecular weights of water and air (0.622)
e, e_a = vapour pressure at surface of drop, and in surrounding air respectively
p = barometric pressure

But the temperature change, dt, resulting from an evaporative mass loss, dm, from a drop of diameter d is:

$$dt = \frac{6\,\ell_v}{\rho_w c_w d^3}\, dm \qquad \text{(B.9)}$$

where ℓ_v = latent heat of vaporization (2.5×10^6 J/kg).

Thus, the rate of change of temperature due to evaporation is:

$$\left.\frac{dt}{d\tau}\right/_{evap} = Nu \frac{6\ell_v D\rho_a}{\rho_w c_w d^2} \frac{M_w}{M_a}\left(\frac{e_a - e}{p}\right) \qquad \text{(B.10)}$$

Combining Expressions (B.7) and (B.10) to obtain the overall rate of temperature change:

$$\frac{dt}{d\tau} = \frac{6\,Nu\,k_a}{\rho_w c_w d^2}(t_a - t)\left\{1 + \frac{M_w \ell_v D \rho_a}{M_a k_a p}\left(\frac{e_a - e}{t_a - t}\right)\right\} \qquad (B.11)$$

$$= \frac{6\,Nu\,k_a}{\rho_w c_w d^2}\,X_t\,(t_a - t) \qquad (B.11a)$$

where X_t is a factor to allow for evaporation:

$$X_t = 1 + 0.622\,\frac{\ell_v}{pc_p}\,\frac{e_a - e}{t_a - t} \qquad (B.12)$$

since $D \simeq \dfrac{k}{\rho_a c_p}$

and where c_p = specific heat of air (1.005×10^3 J/kgK).

Since X_t is a weak function of temperature, Expression (B.11a) may be integrated assuming X_t is a constant, resulting in:

$$\ell n\,\frac{(t_a - t_d)}{(t_a - t_w)} = -\frac{6\,Nu\,k_a}{\rho_w c_w d^2}\,X_t\,\tau \qquad (B.13)$$

or $$t_d = t_a + (t_w - t_a)\,e^{\left(-\frac{6\,Nu\,k_a}{\rho_w c_w d^2}X_t\,\tau\right)} \qquad (B.14)$$

where t_d is the water drop temperature at time τ.

To test the validity of the assumption that the factor X_t may be treated as a constant in the integration, results obtained using Equation (B.14) are compared in Figure B.1 with the results of a numerical integration of Equation (B.11). Also shown for comparison is the effect of ignoring the evaporative effect (convection only). It is clear that the assumption of a constant X_t does not result in any serious errors in the computation of drop temperature.

The appropriate time or distance of flight of a drop before striking some part of the ship is uncertain, as is also a representative drop diameter. Clearly, larger drops will stay airborne for shorter times than smaller drops, so that, together with the increase in the value of the time constant $\left(\dfrac{\rho_w c_w d^2}{6\,k_a\,Nu}\Big/ X_t\right)$ in Equation (B.14) resulting from a larger d, larger drops experience considerably less cooling than smaller drops, a circumstance which results at times in the decks and lower parts of a vessel experiencing little ice build-up while appreciable ice forms on rigging and superstructure.

For the sake of this analysis, however, an effective drop diameter of 2 mm is assumed. It is further assumed that the effective relative velocity between the drop and its surrounding air is the fall velocity of the drop, which for a 2 mm drop is 6.5 m/s (see Ref. 51). Thus, using the expression for the convective heat transfer for a sphere given by McAdams (Ref. 52) i.e. $Nu = 0.37\ Re^{0.6}$, the Nusselt number is 23 and hence the time constant is approximately $5/X_t$ seconds.

The flight time of the drops, τ, was expressed in Reference 42 as x/V (i.e. the distance carried by wind of velocity V) and it was suggested that x might be related to vessel length as a means of introducing vessel size into the analysis however, this is perhaps not the appropriate place to introduce size since the effect would be of increasing icing rate with increasing vessel length, a situation that does not always accord with observation. Perhaps some modification to the liquid water content expression (Eq. (B.3)) would be the more appropriate way of introducing both the size and lines of the vessel. More knowledge of the effect of size and lines on the rate of icing is first needed.

In this analysis the flight distance, x, is assumed constant at 20 m, whence the effective flight time of the drops, τ, becomes 20/V, a figure that results in the best correlation between the analytical and observed rates of icing.

The surface temperature, t_s, was stated earlier to be the equilibrium freezing temperature of water of the appropriate salinity. As ice forms at the surface, salt is rejected from the ice crystal lattice so formed, and the water film on the surface of the ice manifests an enriched salt content. Since a definite relationship exists between the salinity and the freezing temperature of the brine, it follows that the surface temperature, t_s, must be that appropriate to the salinity of the brine on the surface of the ice, and not that appropriate to the parent sea water, t_f. Further, Tabata (Ref. 2) has shown that the chlorinity and freezing temperature of the brine run-off is a function of the freezing fraction, $n(= R_i/R_w)$. In fact his data suggests the simple relationship;

$$t_s = (1 + n)\, t_f \qquad \text{(B.15)}$$

although this likely does not hold as $n \rightarrow 1$.

The freezing temperature is related to the salinity by:

$$t_f = -0.002 - 0.0524S - 6.00 \times 10^{-5} S^2 \qquad \text{(B.16)}$$

where S is in parts per thousand.

This expression is within 0.002°C of the values given in Reference 39 for salinities between 0‰ and 40‰.

Thus, incorporating Equations (B.2) and (B.3a) in Equation (B.6):

$$q_w = 1.7 \times 10^{-7}\, H_w c_w V (t_d - t_s) \qquad \text{(B.6b)}$$

where t_d and t_s are given by Equations (B.14), (B.15) and (B.16).

B.1.3 The Convective Heat Term, q_c

The convective heat transfer is expressed in terms of a heat transfer coefficient, h, and the temperature difference between the surface and the surrounding air:

$$q_c = h\,(t_a - t_s) \qquad \text{(B.17)}$$

In determining an expression for the convective heat transfer coefficient, a certain amount of approximation is necessary since the shape and size of the icing surface is undefined.

For a flat plate in turbulent flow parallel to its surface (c.f. the deck of a vessel) an average heat transfer coefficient over a length L is given (Ref. 53) by:

$$h = 0.037 \frac{k_a}{L} Pr^{1/3} Re^{0.8} \tag{B.18}$$

If a mean "film" or boundary layer air temperature of -5°C is assumed, this expression reduces to:

$$h = 6.44 \frac{V^{0.8}}{L^{0.2}} \ W/m^2K \tag{B.19}$$

In the case of a cylinder of diameter D in crossflow at a Reynolds number of between 50,000 and 200,000 the heat transfer coefficient may be expressed (Ref. 54) by:

$$h = 0.0208 \frac{k_a}{D} Re^{0.814} \tag{B.20}$$

An expression that provides the same index to the Reynolds No. as in Equation (B.18) and is within 1% of Equation (B.20) over its applicable Reynolds number range is:

$$h = 0.0244 \frac{k_a}{D} Re^{0.8} \tag{B.21}$$

which at a mean film temperature of -5°C reduces to:

$$h = 4.75 \frac{V^{0.8}}{D^{0.2}} \ W/m^2K \tag{B.22}$$

Expressions (B.20) through (B.22) are appropriate to smooth cylinders in air flows of low turbulence. The effect of roughness and of free-stream turbulence can be considerable (Ref. 54), and since the air flow over a ship is highly turbulent, it does not seem unreasonable to increase the coefficient of Equation (B.22) arbitrarily and equate it to that of Equation (B.19). If then a characteristic dimension is arbitrarily chosen as 3 m in each case, there results the expression for both flat and cylindrical surfaces:

$$h = 5.17 \ V^{0.8} \ V/m^2K \tag{B.23}$$

Because of the power (0.2) to which the characteristic dimension is raised, the heat transfer coefficient, h, is not very sensitive to this dimension, being within 10% of its nominal value given by Equation (B.23) for values of L from 1.8 m to 5 m.

Equation (B.17) can finally be written:

$$q_c = 5.17 \ V^{0.8} \ (t_a - t_s) \tag{B.24}$$

where t_a is the air temperature, and

t_s is the surface temperature defined by Equation (B.15).

B.1.4 The Evaporative Heat Term, q_e

The evaporative heat transfer, q_e, can be evaluated by analogy with the convective heat transfer (Ref. 52):

$$q_e = h\left(\frac{Pr}{Sc}\right)^{.63} \frac{\epsilon \ell_v}{p\, c_p} (e_a - e_s) \qquad \text{(B.25)}$$

where
Pr = Prandtl number = 0.711
Sc = Schmidt number = 0.595
ϵ = ratio of molecular weights of water vapour and dry air (0.622)
p = atmospheric air pressure
ℓ_v = latent heat of vaporization of water (2.5×10^6 J/kg)
c_p = specific heat of dry air (1.005×10^3 J/kgK)
e_a, e_s = saturation vapour pressure of moist air at temperature t_a, t_s respectively.

Evaluation of $\left(\frac{Pr}{Sc}\right)^{.63}$, ϵ, ℓ_v and c_p results in:

$$q_e = 1731 \frac{h}{p} (e_a - e_s) \qquad \text{(B.26)}$$

and if, as before, $h = 5.17\ V^{0.8}\ W/m^2K$

and assuming $p = 100$ kPa

then:

$$q_e = 89.5 (e_a - e_s)\ V^{0.8}\ W/m^2 \qquad \text{(B.27)}$$

where e_a and e_s are in kPa, and V is in m/s.

The saturation vapour pressure, e, may be expressed in kPa as a function of temperature, t(°C), by:

$$e = \left(\left((1.9226 \times 10^{-7} t + 2.4545 \times 10^{-5})t + 1.4224 \times 10^{-3}\right)t + 0.044436\right)t + 0.61094 \qquad \text{(B.28)}$$

This 4th order polynomial regression equation is within ¼% of the values given in Reference 39 in the temperature range −25°C to +10°C.

B.1.5 The Conductive Heat Term, q_a

In this analysis the heat conducted, q_a, to or from the icing surface through the ice layer and the underlying structure will be assumed negligible, although frequently instances may be observed on iced ships of inadequately insulated crew spaces, as indicated by a lesser quantity of ice in these areas, thus clearly indicating that in these instances heat is being conducted through the structure.

B.2.0 The Total Heat Balance and Rate of Icing

The overall heat balance (Eq. (B.1)) may now be written using Equations (B.5), (B.6b), (B.24) and (B.27):

$$\ell_f R_i + 0.68\, H_w V(t_d - t_s) + 5.17 V^{0.8} \left\{(t_a - t_s) + 17.3\,(e_a - e_s)\right\} = 0 \qquad \text{(B.29)}$$

and evaluating ℓ_f as 3.33×10^5 J/kg, the rate of icing is given by:

$$R_i = 2.04 \times 10^{-6} H_w V(t_s - t_d) + 1.55 \times 10^{-5} V^{0.8} \left\{(t_s - t_a) + 17.3\,(e_s - e_a)\right\} \text{kg/m}^2\text{s} \qquad \text{(B.30)}$$

Or, alternatively in terms of rate of growth of ice thickness, N_i:

$$N_i = \frac{R_i}{\rho_i} = 2.3 \times 10^{-9} H_w V(t_s - t_d) + 1.74 \times 10^{-8} V^{0.8} \left\{(t_s - t_a) + 17.3\,(e_s - e_a)\right\} \text{m/s} \qquad \text{(B.31a)}$$

where the density of ice, ρ_i, is assumed to be 890 kg/m^3.

If the rate is to be expressed in the more convenient units of mm/h, then:

$$N_i^* = 8.26 \times 10^{-3} H_w V(t_s - t_d) + 6.28 \times 10^{-2} V^{0.8} \left\{(t_s - t_a) + 17.3\,(e_s - e_a)\right\} \text{mm/h} \qquad \text{(B.31b)}$$

In these equations the wave height, H_w, is in metres, the relative wind velocity, V, is in m/s, the temperatures are in °C and the vapour pressures are in kPa.

If, as is more usual, the velocity is given in knots, Equation (B.31b) becomes:

$$N_i^* = 4.25 \times 10^{-3} H_w V_{kt}(t_s - t_d) + 3.69 \times 10^{-2} V_{kt}^{0.8} \left\{(t_s - t_a) + 17.3\,(e_s - e_a)\right\} \text{mm/h} \qquad \text{(B.31c)}$$

To test this model of icing under conditions of sea spray, the icing rate as calculated by Equation (B.31c) using the conditions applicable to 39 reported icing incidents (Table VIII) has been compared in Figure 43 with the mean icing rates derived from these reports.

B.3.0 Practical Implementation of the Rate of Icing Equation

In evaluating those expressions that depend on the vapour pressure of the atmosphere (i.e. Eq. (B.12), the evaporation factor in the drop cooling equation, and Eq. (B.27), the evaporative heat term in the heat balance at the icing surface), it has been assumed that the air is 90% saturated rather than saturated, so that in both Equations (B.12) and (B.27) the term e_a is replaced by the expression $0.9\, e_a$.

Because, from Equation (B.15), the effective surface temperature, t_s, is a function of the freezing fraction, $n(=R_i/R_w)$ and hence a function of the, as yet unknown, icing rate, it is necessary to employ a simple iterative procedure to determine the appropriate value of t_s to use in Equations (B.6), (B.24) and (B.28). The initial value of the freezing fraction, n, was assumed to be zero, i.e. $t_s = t_f$. Subsequent iterations used the computed value of R_i (Eq. (B.30)) to determine a new value of n, until successive values of n differed by less than an arbitrary amount (0.0001 was used). If n assumed a negative value, it was set at zero and no icing was inferred.

Similarly, in determining the final drop temperature, t_d, it was initially set at the sea-water temperature, t_w, and a value of X_t (Eq. (B.12)) computed; this was in turm employed in Equation (B.14) to derive a new value of t_d to be used in Equation (B.12). This procedure was repeated until successive values of t_d differed by less than an arbitrary amount (again 0.0001°C was used).

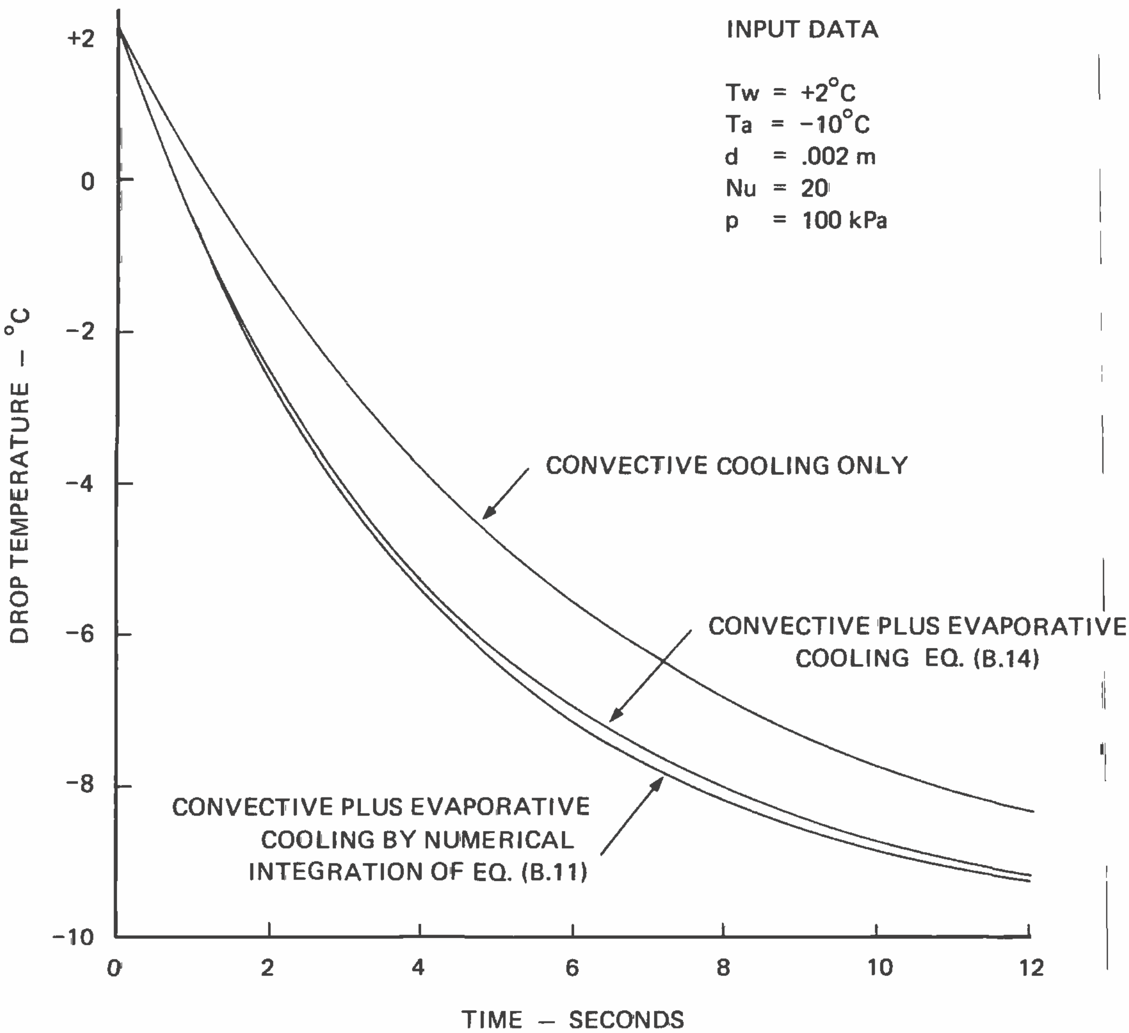


FIG. B.1: COOLING OF 2 MM DIAMETER WATER DROPS FALLING AT TERMINAL VELOCITY THROUGH AIR OF TEMPERATURE -10°C INITIAL DROP TEMPERATURE +2°C

APPENDIX C

BIBLIOGRAPHY

-- Trawler Icing Research, BSRA Report 221, British Shipbuilding Research Association, London, England, 1957.

-- Oceanographic Atlas of the Polar Seas, Part II, Arctic. U.S. Navy Hydrographic Office, Publication No. 705, Part II. 1958.

-- De-icing of Ships' Structures. Report of Trials. Ministry of Defence (U.K.), D.G.S. XC 104, March 1960.

-- Electro-Thermal Heating System for Protection of Aircraft and Ships against Icing. Polar Record, Vol. 10, No. 64, 1960, pp. 68-70.

-- A Shipboard Icing Observations Questionnaire for Gathering and Correlating Shipboard Ice Formation and Weather Information. U.S. Naval Applied Science Lab., Technical Memorandum No. 1 (AD 602016), July 1974.

-- Handbuch für die Fischereigebiete des Nordwest-Atlantischen Ozeans — Westküste Grönland, Hudson-Strasse, Baffin-Land, Labrador, Belle Isle-Strasse, Neufundland, Nova Scotia. Deutschen Hydrographischen Institut, Seehandbuch Nr. 2066, Hamburg, August 1964.

-- Oceanographic Atlas of the North Atlantic Ocean, Section II, Physical Properties. U.S. Naval Oceanographic Office, Publications No. 700, 1967.

-- Combatting the Icing Problem. World Fishing, December 1968, p. 48.

-- Recommendation on Intact Stability of Fishing Vessels. Intergovernmental Maritime Consultative Organization, London, 1969.

-- De-icing Equipment for Trawlers. Sea Harvest and Ocean Science, December 1969/January 1970, p. 23.

-- De-icing Apparatus for Ships. Polar Record, Vol. 15, No. 96, 1970, pp. 343-4.

-- Seminar on Trawler Safety. Naval Scientific and Technical Information Centre, U.K., NSTIC/18990, 1970.

Archibald, D.C. Intense Storm Tracks over Hudson Bay, the Eastern Nova Scotia Coast and the Grand Banks. Canadian Inst. Mining and Metallurgy, Special Vol. 10, "Ice Seminar", 1969, pp. 36-44.

Bardarson, H.R. Icing of Ships. Jokull (Iceland), Vol. 19, 1969, pp. 107-120.

Berembeym, D. Ya. Hydrometeorological Conditions of Ship Icing (in Russian). Meteorologiya i Gidrologiya, No. 5, 1969, pp. 99-104.

Berry, M.O.
Dutchak, P.M.
Lalonde, M.E.
McCulloch, J.A.W.
Savdie, I.
Weather, Waves and Icing in the Beaufort Sea. Beaufort Sea Project, Dept. of the Environment, (Canada), Technical Report No. 21, Dec. 1975.

Borisenkov, E.P. et al
Investigation of the Physical Nature of Ship Icing. (A collection of 19 papers. Translation of Russian-language book: Issledovaniye Fizicheskoy Prirody Obledeneniya Sudov, Leningrad, 1972), U.S. Army, Cold Regions Research and Engineering Laboratory, Draft Translation 411, 1974.

Borisenkov, E.P. (eds.)
Pchelko, I.G.
Indicators for Forecasting Ship Icing. U.S. Army, Cold Regions Research and Engineering Laboratory, Draft Translation 481 (AD-A030 113), 1975.

Comiskey, A.
Vessel Icing — Know When to Expect It. Alaska Seas and Coasts, Vol. 4, No. 5, Dec. 1976, pp. 6-7.

Dacam, D.J.
Ice Accretion on Ships. In: Seminar on Trawler Safety, Naval Scientific and Technical Information Centre, U.K., NSTIC/28990, 1970, pp. 3-8.

Dunbar, M.
Geographical Distribution of Superstructure Icing in the Northern Hemisphere. Defence Research Board, Canada, Report No. Misc. G-15, Sept. 1964.

Eidel'man, D. Ya.
Icing of Ships at Sea. (in Russian), Rybnoye Khazyaystvo, No. 1, 1966, pp. 33-35.

Eidel'man, D.
The Icing Hazard of Seagoing Ships. (in Russian). Morskoy Flot, Vol. 16 (10), Oct., 1966, pp. 26-27.

Fein, N.
Freiberger, A.
A Survey of the Literature on Shipboard Ice Formation. Naval Engineers Journal, Dec. 1965, pp. 849-855.

Ford, T.F.
Nichols, O.D.
Adhesion-Shear Strength of Ice Frozen to Clean and Lubricated Surfaces. U.S. Naval Research Laboratory, Report 5832, August 1962.

Freiberger, A.
Lacks, H.
Ice-Phobic Coating for De-icing Naval Vessels. Naval Research Reviews, May 1961, pp. 1-7.

Guttman, N.B.
Study of Worldwide Occurrence of Fog, Thunderstorms, Supercooled Low Clouds and Freezing Temperatures. National Oceanic and Atmospheric Administration (U.S.A.) for Naval Weather Service Command, NAVAIR-50-1C-60, Dec. 1971.

Harwood, T.A.
The Fallout Hazard in Icing Conditions. Proceedings of Tripartite Symposium on Technical Status of Radiological Defense in the Fleets, U.S. Radiological Defense Laboratory, Vol. 1, R & L No. 103, May 1960, pp. 173-185.

Hay, R.F.M.
Meteorological Aspects of the Loss of LORELLA and RODERIGO. Marine Observer, Vol. 26, No. 172, April 1956.

Hay, R.F.M.
Ice Accumulation upon Trawlers in Northern Waters. Meteorological Magazine, London, Vol. 85, 1956, pp. 225-229.

Holland-Martin, Sir. D.
Trawler Safety. Final Report of the Committee of Inquiry into Trawler Safety. Cmmd. 4114 H.M.S.O., (London), July 1969.

Itagaki, K. — Icing on Ships and Stationary Structures under Maritime Conditions. A Preliminary Literature Survey of Japanese Sources. U.S. Army, Cold Regions Research & Engineering Laboratory, Special Report No. 77-27, 1977.

Kultashev, Ye. N.; Panov, V.V. — Possibility of Determining the Length of Time a Fishing Vessel should Stay in an Icing Zone. (in Russian). Problemy Arktiki i Antarktiki, Vol. 32, 1969, pp. 94-9.

Kachurin, L.G.; Gashin, L.I.; Smirnov, I.A. — Icing Rate of Small Displacement Fishing Boats under Various Hydro-meteorological Conditions. Meteorologiya i Gidrologiya, Moscow, No. 3, 1974, pp. 50-60.

Jacobs, L. — Frost Smoke. Marine Observer, Vol. 24, 1954, pp. 113-4.

Kings, R.D. — Hyviz — A New High Light Transmission and Electrically Conducting Film for Heating of Ships' Bridge Windows. Marine Engineers Review, May 1973, pp. 37-38.

Landy, M.; Freiberger, A. — Theory of Ice Adhesion, Part I. Adhesion of Ice to Plastics. U.S. Naval Applied Science Laboratory, Progress Report 1, June 1965.

Landy, M.; Freiberger, A. — An Approach to the Shipboard Icing Problem. Naval Engineers Journal, Vol. 80, No. 1, 1968, pp. 63-72.

Lange, R. — Spritzwasservereisung auf den Fischgründen vor West-Grönland und Neufundland. Wetterlotse, Vol. 17, No. 220, 1965, pp. 63-70.

Lee, A. — Ice Accumulation on Trawlers in the Barents Sea. Marine Observer, Vol. 28, No. 181, 1958, pp. 138-142.

Lock, G.S.H. — Some Aspects of Ice Formation with Special Reference to the Marine Environment. Paper presented to the North-East Coast Institution of Engineers and Shipbuilders, Newcastle-upon-Tyne, April 1972.

McLeod, W.R. — Atmospheric Superstructure Ice Accumulation Measurements. Proc. of 9th Annual Offshore Technology Conf., 1977.

Mertins, H.O. — Icing of Fishing Vessels due to Spray. Marine Observer (London), Vol. 38, No. 221, 1968, pp. 128-130.

Minsk, L.D. — Ice Accumulation on Ocean Structures. U.S. Army, Cold Regions Research and Engineering Laboratory, Report 77-17, Aug. 1977.

Nemoto, T. — On the Icing of Ships and its Effect on Stability. (in Japanese with English abstract). Jour. of Nautical Society of Japan, Vol. 26, 1961, pp. 87-93.

Oliver, R.C. — Trawlermen's Handbook. Fishing News (Books) Ltd., 2nd Revised Edition, 1975.

Ono, N. — Studies of Ice Accumulation on Ships. Part II. Conditions of Icing and Accreted Ice Weights. National Research Council of Canada, Technical Translation TT-1319, 1968. (Also published as Defence Research Board, Canada, Translation No. T94J, Nov. 1967).

Ono, N. — Studies on Ice Accumulation on Ships. IV. Statistical Analysis of Ship-Icing Conditions. (In Japanese, with English summary). Low Temperature Science, Ser. A, Vol. 32, 1974, pp. 236-242.

Persechino, M.A. — Valveless Pulsejet De-icer Application. U.S. Naval Research Laboratory, Report 5024, Nov. 1957.

Sawada, T. — Ice Accretion on Ships in Northern Seas of Japan. Journal of the Meteorological Society of Japan, Vol. 46, No. 3, 1968, pp. 250-254.

Shekhtman, A.N. — Hydrometeorological Conditions in the Icing-up of Vessels at Sea. Naval Scientific and Technical Information Centre, (U.K.), Translation No. 2311, 1971.

Shekhtman, A.N. — The Probability and Intensity of the Icing-up of Ocean-Going Vessels, Naval Scientific and Technical Information Centre (U.K.), Translation No. 2312, April 1971.

Small, T.V. — Icing at Sea. Journal of the Royal Naval Scientific Service, Vol. 26, 1971, pp. 364-371.

Stallabrass, J.R., Hearty, P.F. — The Icing of Cylinders in Conditions of Simulated Freezing Sea Spray. National Research Council Canada, Report MD-50, 1967.

Stallabrass, J.R. — Methods for the Alleviation of Ship Icing. National Research Council Canada, Report MD-51, 1970.

Stallabrass, J.R. — Meteorological and Oceanographic Aspects of Trawler Icing off the Canadian East Coast. The Marine Observer, London, Vol. 41, 1971, pp. 107-121.

Stallabrass, J.R. — Trawler Icing off Eastern Canada. National Research Council Canada, Report No. LTR-LT-50, 1973.

Stallabrass, J.R. — Icing of Fishing Vessels in Canadian Waters. National Reserach Council Canada, DME/NAE Quarterly Bulletin No. 1975(1), April 1975, pp. 25-43.

Stallabrass, J.R. — Icing of Fishing Vessels: An Analysis of Reports from Canadian East Coast Waters. National Research Council Canada, Report No. LTR-LT-98, 1979.

Tabata, T., Iwata, S., Ono, N. — Studies of Ice Accumulation on Ships. Part I. National Research Council Canada, Technical Translation TT-1318, 1968. (Also published as Defence Research Board, Canada, Translation No. T93J, 1967).

Tabata, T. — Research on Prevention of Ship Icing. Defence Research Board, Canada, Translation No. T95J, July 1968.

Tyurin, A.P. — On the Problem of Methods of Observing Icing on Ships of the Fishing Industry Fleet, (in Russian). Meteorologiya i Gidrologiya, No. 2, 1969, pp. 108-110.

Van Praagh, G. — De-icing of Ships. Science News, Vol. 4, 1947, pp. 72-6.

Vasil'yeva, G.V. — Hydrometeorological Conditions Causing Ice Accretion on Ships. Defence Research Board, Canada, Translation No. T486R, 1967.

Wise, J.L., Comiskey, A.L. — Superstructure Icing in Alaskan Waters. U.S. Dept. of Commerce, NOAA Special Report, April 1980.

Yerokhin, Ye. Safety of Shipping under Icing Conditions. Defence Research Board, Canada, Translation No. T485R, 1968.

Zakrzewski, W. Zapobieganici Zwalczanie Oblodzenia Statków Morskich (Prevention and Fighting against Ice Accretion on Sea-going Ships). (in Polish). Technika i Gospodarka Morska, No. 3, 1980, pp. 143-146.

Zakrzewski, W. Prosty Sposób Okréslania Masy Lody na Oblodzonym Statku (A Simple Method for Determining the Mass of Ice on an Ice-covered Ship). (in Polish). Polska Akademia Nauk, Instytut Nawigacji Morskiej. III Kurso-konferencja Meteorologii Morskicj. Szczecin, 1980, pp. 138-141.