# ARCTIC SEA ICE OF VARIOUS AGES

## I. ULTIMATE STRENGTH

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Abstract. A comparison of polar ice (several years old) with biennial ice (between one and two years old) was made in the field at lat. 79°N., long. 104°W. Vertical cores were extracted from the ice cover and sectioned. Their ultimate tensile strengths were measured by the ring-tensile method. Supporting measurements were made of the salinity, density, and crystal structure of the ice. Tensile strength values averaged 6 per cent higher for the polar ice and 21 per cent higher for the biennial ice than comparable results for annual sea ice. A few horizontal cores of biennial ice were analysed similarly with inconclusive results.

Résumé. On a comparé sur le terrain (79°N, 104°W) la glace polaire datant de plusieurs années et la glace ayant entre une et deux années d'âge. Des témoins verticaux de glace ont été extraits de la couverture et sectionnés. Leur résistance à la rupture a été mesurée par la méthode du "ring-tensile". On a fait des mesures complémentaires de salinité, densité et structure cristallographique de la glace. Les résultats de la résistance à la tension sont en moyenne de 6% plus élevés pour la glace polaire et de 21% plus élevés pour la glace agée de 2 ans que ceux obtenus pour la glace de mer annuelle. On a obtenu aussi quelques témoins horizontaux de glace datant de deux ans; les résultats d'analyses semblables ne se sont pas révélés concluants.

Zusammenfassung. In der Arktis wurde auf 79° n. Br. und 104° w. L. eine Vergleichsuntersuchung zwischen Polareis (mehrere Jahre alt) und zweijährigem Eis (1–2 Jahre alt) vorgenommen.
Vertikale Eiskerne wurden aus der Eisdecke gebohrt und in Scheiben zerschnitten. Ihre maximale Zugfestigkeit wurde durch die Ringtensionsmethode gemessen. Zusätzlich wurde der Salzgehalt, die Dichte und die Kristallstruktur bestimmt. Verglichen mit Resultaten von einjährigem Meer-Eis lagen die Zugfestigkeitswerte im Durchschnitt für Polareis um 6% und für zweijähriges um 21% höher. Einige horizontal ausgebohrte Eiskerne des zweijährigen Eises wurden auf ähnliche Weise analysiert, jedoch ohne bemerkenswerte Ergebnisse.

### 1. Introduction

The work to be described was carried out between mid-April and mid-May 1962 when the McGill Ice Research Project fielded an expedition in the vicinity of Isachsen, Ellef Ringnes Island, N.W.T. Five members of the Project participated, and logistic support was received from the Royal Canadian Air Force and the Polar Continental Shelf Project of the Department of Mines and Technical Surveys.

According to limited records available from the meteorological observers at Isachsen, there was reason to expect a better than even probability of finding sea ice of various ages, i.e. young sea ice to old pack ice, in the immediate area. This would have afforded the opportunity of obtaining and comparing measurements of some of the properties of sea ice as a function of its age. Unfortunately, it was found that the bay had not cleared the previous summer. The ice sheet, formed in the winter of 1960–61 was very much in evidence and no new or annual ice could be located. An air survey did reveal some large polar floes, the closest being within what was considered to be a safe operating distance for a single J-5 vehicle, the only ground transport at our disposal.

A trail was marked leading over the extensive and relatively flat sheet of biennial ice and a camp was established near the edge of a polar ice floe, about a hundred yards beyond the sheet of biennial ice. The biennial ice was almost free of pressure ridges and comparatively easy to traverse. Its thickness was later found to be about 2·8 to 3·0 m. The polar ice was well-weathered, its surface covered with gently rounded hummocks of height about 1 m., spaced at intervals of about 30 m. The thickness of the level sections of the polar ice was about 3·5 m. The snow cover was heavy in the vicinity of the camp site, varying between 50 and 100 cm. in depth. Two wannegans were hauled to the site to serve as living and working



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quarters, and a tent was used for additional sleeping quarters. It is estimated that the camp was situated at lat. 78°42′N., long. 104°06′W.

The observations made were therefore limited to biennial ice of age slightly less than two years and older pack ice of undetermined age. They consisted principally of measurements of elastic parameters, which are reported elsewhere (Pounder and Langleben, 1964), and of ultimate tensile strength of sections of vertical cores extracted from the ice sheets. In addition, supporting measurements of salinity, temperature and density were made.

The thickness of the biennial ice and the manpower and equipment situation were such as to permit extraction of horizontal cores. A pit large enough to operate the coring auger in a horizontal attitude was excavated. Its dimensions were roughly 1·5 m. long by 60 cm. wide by 1 m. deep. It proved difficult to core horizontally, a lot of the ice coming out as fragments too short to be of use. Nevertheless, sufficient coring was done at two levels (67 and 86 cm. below the ice surface) to produce about forty samples suitable for strength test measurements.

## 2. Experimental Methods

The ultimate strength was determined using the *ring tensile test*. The theory of this method of finding the ultimate tensile strength is discussed by Ripperger and Davids (1947); the experimental detail as applied to ice is described by Butkovich (1958), Assur (1958), Langleben (1959), and Graystone and Langleben (1963). Its application to ice mechanics originates with the introduction of the SIPRE coring auger. This most convenient tool for extracting ice from the ice sheet has become very widely adopted.

All the equipment used in this study was similar to that described by Graystone and Langleben (1963). The sample preparation and testing proceeded in the following manner. A 3-in. (7·6-cm.) diameter core was extracted from the ice sheet. It was sectioned into samples of very nearly 3-in. length and a hole of diameter 0·5 in. (1·27 cm.) was drilled along the axis of each sample. The sample was placed in a screw-jack type of press with its axis horizontal and the direction of load application was perpendicular to the axis of the sample. Upon breakage, the fragments of the sample (usually in the form of two half-cylinders) were put into a sealed container and set aside for subsequent determination of salinity by titration.

## 3. Observations and Results

The prediction (Anderson, 1958; Assur, 1958) that the tensile strength of sea ice varies with the square root of its brine content as a fraction of the total volume has been verified by Assur (1958), Weeks (1962) and Graystone and Langleben (1963). As yet, there is no agreement on values of tensile strength nor on its rate of decrease with increasing brine content. The results of the present study on biennial and polar sea ice are therefore compared with those of Graystone and Langleben (1963) on annual ice, since the equipment used and the methods of measurement and analysis were virtually identical in both cases.

### *Vertical cores*

Eighty-seven samples of biennial ice and 132 of polar ice, all from vertical cores, were tested. Distinguishing between biennial and polar ice, the data on ultimate tensile strength were listed against the square root of the brine content of the samples in increasing order of brine content $\nu$. Averages of $\nu^{\frac{1}{2}}$ and of tensile strength $\sigma_m$ were taken in intervals of 0·01 in $\nu^{\frac{1}{2}}$. The results are shown in the first three columns of Table I, Parts A and B.

As seen from Table I, the brine contents did not quite attain 1% ($\nu^{\frac{1}{2}} < 0{\cdot}1$) whereas the data analysed by Graystone and Langleben (1963) included brine contents of up to 10% by volume. The low brine contents are attributed partly to low salinities (less than

1‰ as compared to about 5‰ for annual ice) and partly to a relatively narrow range of ice sample temperatures (−10° C. to −15° C.), sufficiently far removed from the freezing point so that variation of brine content with temperature is small.

On the basis of the small range of brine content it would be unrealistic to draw inferences about the dependence of tensile strength on brine content for the biennial and polar ice.

TABLE I. THE AVERAGE MEASURED TENSILE STRENGTH $\sigma_m$ FOR $n$ SAMPLES OF AVERAGE BRINE CONTENT BY FRACTION OF VOLUME $\nu$ COMPARED WITH $\sigma_a$, THE CALCULATED STRENGTH FOR ANNUAL ICE OF THE SAME BRINE CONTENT

| $n$ | $\nu^{\frac{1}{2}}$ | $\sigma_m$ kg. cm.$^{-2}$ | $\sigma_a$ kg. cm.$^{-2}$ | $(\sigma_m-\sigma_a)/\sigma_a$ per cent |
|---|---|---|---|---|
| *Part A: Biennial ice* | | | | |
| 7 | 0·0370 | 31·1 | 27·0 | 15·1 |
| 11 | 0·0468 | 31·0 | 26·5 | 16·9 |
| 43 | 0·0545 | 32·1 | 26·1 | 23·0 |
| 16 | 0·0651 | 31·4 | 25·5 | 23·1 |
| 10 | 0·0749 | 30·1 | 25·0 | 20·4 |
| 87 Total | | Weighted average percentage difference = | | 21 |
| *Part B: Polar ice* | | | | |
| 3 | 0·0258 | 26·2 | 27·6 | − 5·0 |
| 5 | 0·0362 | 25·4 | 27·1 | − 6·2 |
| 9 | 0·0461 | 24·3 | 26·5 | − 8·3 |
| 20 | 0·0554 | 24·7 | 26·0 | − 5·0 |
| 46 | 0·0655 | 28·2 | 25·5 | 10·6 |
| 33 | 0·0739 | 29·0 | 25·0 | 16·0 |
| 10 | 0·0854 | 25·3 | 24·4 | 3·7 |
| 6 | 0·0953 | 21·9 | 23·9 | − 8·7 |
| 132 Total | | Weighted average percentage difference = | | 6 |
| *Part C: Polar ice subjected to stress during coring* | | | | |
| 3 | 0·0453 | 22·6 | 26·5 | −14·7 |
| 7 | 0·0546 | 20·3 | 26·1 | −22·1 |
| 8 | 0·0646 | 20·1 | 25·6 | −21·5 |
| 6 | 0·0727 | 21·9 | 25·1 | −12·8 |
| 5 | 0·0862 | 22·8 | 24·4 | − 6·6 |
| 4 | 0·0977 | 20·2 | 23·8 | −16·0 |
| 33 Total | | Weighted average percentage difference = | | 16 |

Rather more significant is a comparison of these strengths with those for annual sea ice of the same brine content and also with each other. A comparison is made in columns 4 and 5 of Table I, Parts A and B, where $\sigma_a$ is the tensile strength value for annual ice taken from the paper of Graystone and Langleben (1963). It would appear that the tensile strengths of biennial ice and polar ice are respectively about 21 per cent and 6 per cent greater on the average than that of annual sea ice.

There is no *a priori* reason to expect that the strengths would be alike. In fact, one would anticipate a progressive change occurring because of seasonal brine seepage and possibly subsequent recrystallization. This could lead to an increase in strength from year to year as the ice aged or to a levelling off in strength after one year if the seepage of brine becomes negligible after the first summer. The strength of polar ice should be equal to or greater than that of biennial ice. The results of Table I show the opposite effect, the strength of the biennial ice exceeding that of the polar ice by about 15 per cent. It is difficult to explain this anomaly. Both types of ice revealed a similar sort of crystal structure, had densities comparable to within less than 1 per cent and indistinguishable elastic constants (Pounder and Langleben, 1964).

*Horizontal cores*

Operating from within the pit excavated in the biennial ice sheet, a few horizontal cores were extracted at depths of 67 and 86 cm. From these it was possible to prepare for each depth about 20 samples suitable for strength tests. The results are shown in the top two rows of Table II. The average strength at each level is almost alike in the two cases and, considering the large standard deviations, the difference is insignificant.

TABLE II. COMPARISON OF STRENGTH OF SAMPLES FROM HORIZONTAL CORES AND VERTICAL CORES

| | *Depth* | *Number of samples* | $\sigma_m$ | *Standard deviation* |
|---|---|---|---|---|
| | cm. | | kg. cm.$^{-2}$ | kg. cm.$^{-2}$ |
| Biennial-horizontal | 67 | 22 | 35·8 | 7·6 |
| Biennial-horizontal | 86 | 19 | 34·6 | 7·5 |
| Biennial-vertical | 67–86 | 18 | 33·9 | 4·7 |
| Polar-vertical | 67–86 | 18 | 30·7 | 4·8 |

The results for samples from the horizontal cores are compared in Table II with results of samples from vertical cores, using for the latter only those samples whose centres of mass were at a depth of between 67 and 86 cm. Comparing biennial horizontal with biennial vertical, it appears that the strength of the former is slightly greater (about 4 per cent) but again the small difference may not be statistically significant. The standard deviation is, however, considerably smaller for the vertical biennial indicating less scatter about the mean than for the horizontal biennial. The last row of Table II, relating to polar ice samples from vertical cores, further illustrates that smaller standard deviations are associated with samples from vertical cores than for those from horizontal cores. The actual distributions of strength values relating to the data of Table II are shown in Figure 1 as histograms of frequency of occurrence of a given deviation from the average or mean strength. It is seen that the histograms associated with vertical cores tend to tail off whereas those pertaining to horizontal cores may very well be flat if the number of samples is large enough.

The data may be explained with reference to the sketches of Figure 2. Sketch (a) shows a typical cross-section of a sample from a vertical core which consists of long vertical filaments or crystals of ice. The load applied in testing develops tension at the top and bottom of the central hole and the cylinder fails at intercrystalline boundaries. For samples from horizontal cores, the load may be applied at a random angle $\theta$ to the vertical axis in the ice, depending on how the samples are placed in the press. Sketch (b) shows a section through a horizontal core sample oriented in the press so that $\theta = 0$. Again failure would be at an intercrystalline boundary and, apart from statistical fluctuations, tests on samples (a) and (b) should yield the same results. Sketch (c) is of a horizontal sample oriented at a random angle $\theta$. Failure here may occur along a slanting intercrystalline boundary or by shear of a single ice crystal at the points of maximum stress. The observed strength would be expected to be higher in this case and to be a function of $\theta$ with a maximum at $\theta = 90°$. Unfortunately the vertical direction was not marked on the horizontal cores so that the $\theta$-dependence could not be verified.

*Cores stressed during coring operation*

The coring auger taken on the expedition turned out to be defective. (Fortunately the Polar Continental Shelf Project was able to provide another coring auger. The latter was used for the major part of the work, which has already been described.) On examination of the defective auger, it was found that the inside of the cutting head had worn to such an extent that the diameter of the ice core produced was approaching in size the diameter of the entrance to the barrel of the corer. Several days were wasted attempting to improve

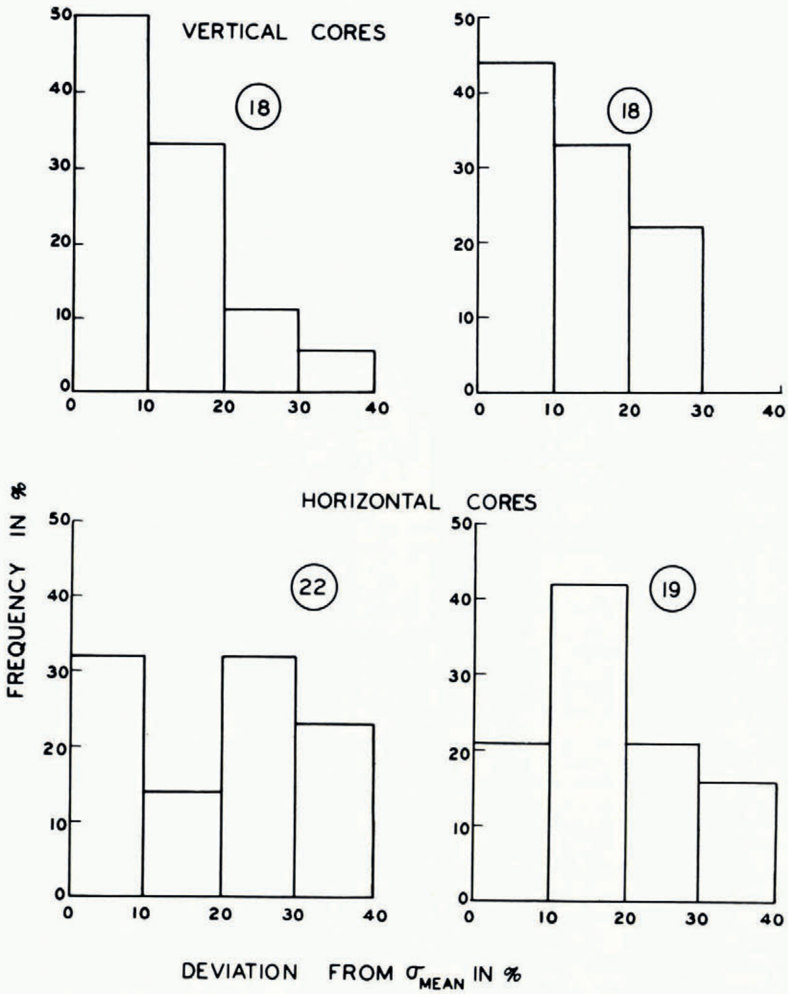


*Fig. 1. Distribution of ultimate strength measurements at selected depths. The two lower histograms refer to horizontal cores in biennial ice at depths of 67 cm. in the left hand diagram and of 86 cm. in the right hand diagram. The upper histograms give comparable distributions for vertical cores from biennial (left) and polar ice (right)*

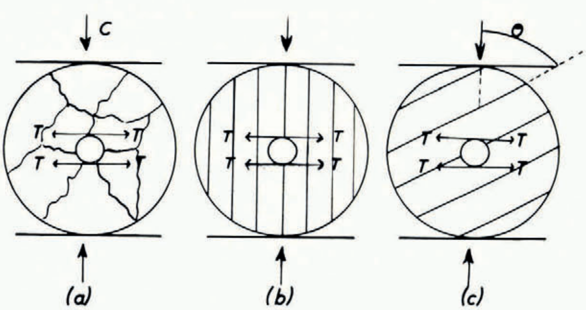


*Fig. 2. Structure of (a) vertical and (b) and (c) horizontal ice cores and the stresses developed in a ring-tensile test*

its performance. The ice core was being subjected to torsion about its axis, the resultant strains frequently exceeding the elastic limit of the ice. The core consisted of small fragments, mostly of about 5 cm. lengths but occasionally running up to about 20 cm. Where fracture did not take place during coring, frequent cracks were evident as planes almost perpendicular to the axis of the core.

Theoretically, the effect of these cracks on the strength as determined by the ring test should be negligible. Theory does not distinguish between say a single 6-cm. long sample or three 2-cm. long samples in contact. Practically it turns out that torsional stresses applied to the ice during coring exert a significant effect on the ring-tensile strength values. Part C of Table I shows such data for 33 samples of polar ice. The strength values are found to be consistently lower than for annual ice, on the average about 16 per cent lower. The strength of the "normal" polar ice samples was, on the other hand, about 6 per cent greater than that of annual ice. There is thus a difference of about 22 per cent in the strength of stressed as opposed to unstressed polar ice.

It is disturbing to find that the coring auger can influence the results to such an extent. The case reported here is perhaps extreme, but the question arises as to whether an ice core completely free of strains can ever be extracted. The notion that the spread of values of ring-tensile strength of sea ice reported by various investigators may be related to the state of the coring auger used bears consideration.

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