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PRELIMINARY STUDIES ON SEA ICE IN McMURDO SOUND, ANTARCTICA, DURING "DEEP FREEZE 65"

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ABSTRACT. The sea ice in McMurdo Sound, Antarctica, is extensively utilized for runways, travel, freight hauling and docking facilities. The safety and efficiency of these operations depend upon a better understanding of the sea-ice bearing strength.

Variations in shear and tensile strength, decreased thickness, salinity changes, internal deterioration and changes of the temperature gradient are all related to and dependent upon snow cover, ambient temperatures and solar radiation. During the austral summer of 1964–65, shear strength decreased from 9·8 kg./cm.^{2} in October to 6·3 kg./cm.^{2} in late January and then increased to 8·0 kg./cm^2. by 10 February. The salinity of collected brine decreased from 125 p.p.t. in November to 43 p.p.t. in January. Thickness increased until mid-December, then decreased rapidly by bottom melting until break-out in February. In the Cape Armitage shoal area, thickness decreased from 2·5 m. in mid-December to 36 cm. in late January. Snow cover significantly affects the degree of internal deterioration and the amount of strength loss during the summer. Sea ice with more than 6 cm. snow cover is consistently stronger than unprotected ice and deterioration is less. Bearing strength of the sea ice is sufficient for most ordinary loads throughout the period of most extensive use.

RÉSUMÉ. *Etudes préliminaires de la glace de mer à McMurdo Sound, Antarctique, pendant l'opération "Deep Freeze 65".* La glace de mer de McMurdo Sound est utilisée comme pistes d'envol, routes, transport de frêt et quais de débarquement. La sécurité et l'efficacité de ces opérations comptent sur une meilleure connaissance des forces de portance de la glace de mer.

Les variations de la résistance au cissaillement et à la traction, la diminution d'épaisseur, les changements de salinité, la détérioration interne et les variations de gradient thermique sont tous liés et dépendants de la couverture de neige, des températures ambiantes et de la radiation solaire. Pendant l'été austral de 1964–65, la résistance au cissaillement diminuait de 9,8 kg/cm^2 en octobre à 6,3 kg/cm^2 fin janvier, puis augmentait à 8,0 kg/cm^2 vers le 10 février. La salinité des échantillons de saumure diminuait de 125 ‰ en novembre à 43 ‰ en janvier. L'épaisseur augmentait jusqu'à mi-décembre, puis diminuait rapidement par fonte sous-glaciaire jusqu'à la rupture en février. Dans les bas fonds de Cape Armitage, l'épaisseur diminuait de 2,5 m vers la mi-décembre à 36 cm fin janvier. La couverture de neige affecte d'une manière significative le degré de détérioration interne et la valeur de la perte de portance pendant l'été. La glace de mer, surmontée d'une épaisseur de neige de plus de 6 cm, est plus résitante que la glace nue et la détérioration est moindre. La force de portance de la glace de mer est suffisante pour la plupart des charges ordinaires pour toute la période d'utilisation active.

ZUSAMMENFASSUNG. *Vorläufige Studien über das Meereis im McMurdo Sound, Antarktika, während "Deep Freeze 65".* Das Meereis des McMurdo Sound erfährt starke Beanspruchung durch Rollfelder, Verkehr, Frachtladung und -lagerung. Die Sicherheit und Leistungsfähigkeit dieser Massnahmen hängt von der besseren Kenntnis der Tragkraft des Meereises ab. Schwankungen in der Scher- und Zugfestigkeit, abnehmende Dicke, Änderungen des Salzgehaltes, innerer Zerfall und Schwankungen des Temperaturgradienten werden in Verbindung und Abhängigkeit zur Schneedecke, den Temperaturen der Umgebung und der Sonneneinstrahlung gebracht. Während des Südsommers 1964/65 nahm die Scherfestigkeit von 9,8 kg/cm^2 im Oktober auf 6,3 kg/cm^2 zu Ende Januar ab, um bis zum 10 Februar wieder auf 8,0 kg/cm^2 anzuwachsen. Der Salzgehalt von Salzwasserproben nahm von 125 ‰ im November auf 43 ‰ im Januar ab. Die Dicke nahm bis Mitte Dezember zu und verminderte sich schnell durch Abschmelzen an der Unterseite bis zum Aufbruch im Februar. Im Gebiet der Sandbank bei Cape Armitage nahm die Dicke von 2,5 m bis auf 36 cm zwischen Mitte Dezember und Ende Januar ab. Die Schneedecke hat entscheidenden Einfluss auf den Grad des inneren Zerfalls und die Festigkeitsabnahme während des Sommers. Meereis mit einer mehr als 6 cm dicken Schneedecke ist beträchtlich fester als Blankeis und sein Zerfall ist geringer. Die Tragfähigkeit des Meereises reicht für die meisten gewöhnlichen Lasten während der Zeit der stärksten Beanspruchung aus.

INTRODUCTION

The sea ice in McMurdo Sound south of McMurdo station, Antarctica, is extensively used for aircraft operations, travel, freight hauling and to provide docking areas for loading and unloading cargo. The safety and efficiency of utilizing the sea ice requires a knowledge of many factors affecting its physical properties and bearing strength. The more important factors influencing the physical properties of the ice can be grouped into two broad classes: extrinsic and intrinsic. The extrinsic factors include solar radiation, tides and currents, water temperature and snow cover. Intrinsic factors include thickness, salinity, amount of deterioration, brine-drainage characteristics, crystallography, temperature, strength, cracks and thermal properties. All of these factors are related to, and in some degree are dependent upon, each other. This preliminary report describes some of these relationships and attempts to show how they affect the strength of the ice.

Location

McMurdo Sound is located at the western extremity of the Ross Ice Shelf and it is part of the Ross Sea that is bounded on the east by Ross Island, the west by the mountains of Victoria Land and the south by the Ross Ice Shelf. McMurdo station is located on the southern tip of Hut Point peninsula and it is about 5 miles (8 km.) north across McMurdo Sound from Williams Field (Fig. 1).

The part of McMurdo Sound south of Hut Point peninsula is covered by ice for at least 10 months per year. The ice reaches a maximum thickness varying between 2·5 and 3·0 m. by mid-December. Surface melting is negligible but in December the ice begins to deteriorate internally and becomes thinner by bottom melting. Usually by mid- to late January, working cracks appear and the ice begins to break up into individual floes. High tides, storms, wind or a combination of such can accelerate the break-out. The maximum break-out commonly occurs in February and the sea is usually frozen over again by late March (Heine, 1963, p. 399).

Testing Methods and Sampling Sites

One of several methods of studying the strength of sea ice is to correlate the results of different kinds of strength tests with either temperature and/or salinity or with brine volume

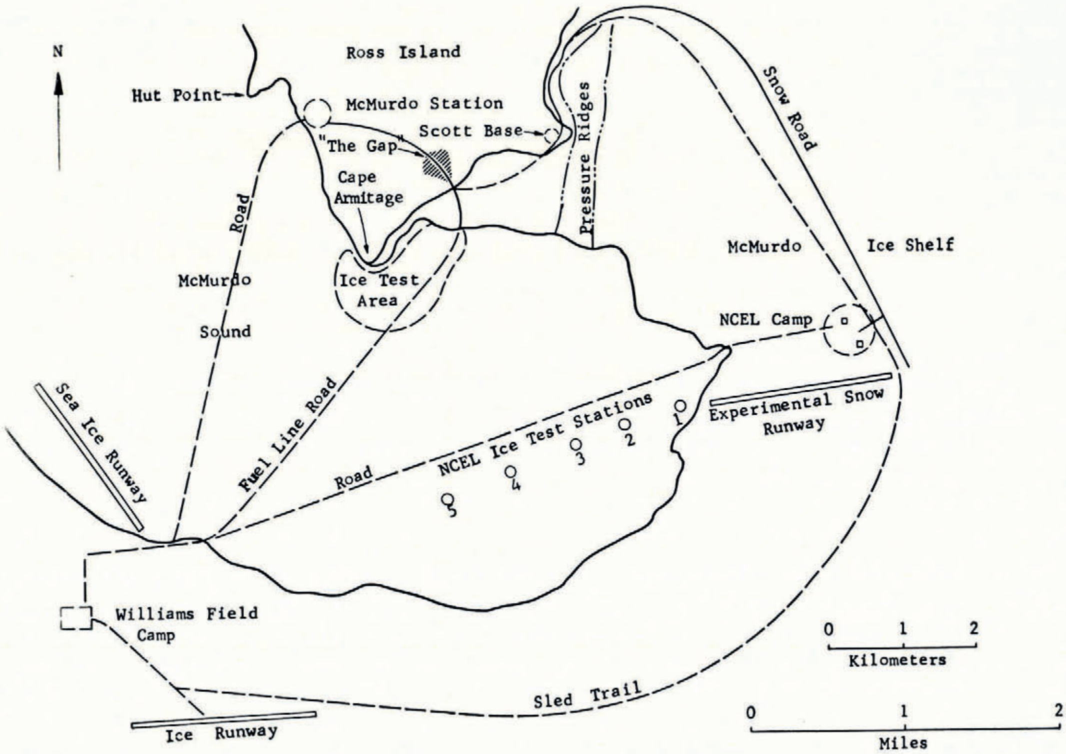

Fig. 1. Index map of the McMurdo Sound area south of Hut Point, Ross Island, Antarctica

which is a function of temperature and salinity. The commonest small-scale strength test used for this purpose is the ring tensile test described by Butkovich (1958) and extensively used in correlation with brine volume by Assur (1956), Graystone (1960), Langleben and Pounder (1964), and others. Other tests that have been used are direct tensile, unconfined compression, semi-confined shear and small-beam tensile tests. Many workers have also attempted to correlate their small-scale tests with strength results produced by breaking large *in situ* ice beams.

Strength data used in this report were obtained from the results of semi-confined shear and ring tensile tests performed on 7·6 cm. long specimens cut from 7·6 cm. diameter cores obtained with a CRREL ice-corer. As our test procedure allowed us to complete the shear or ring tensile tests within 4 min. from the time the specimens were removed from the sea-ice sheet, we assume that our test temperatures are identical to the *in situ* temperatures. The ring-tensile tests were performed in the manner described by Weeks (1962). The shear apparatus (Fig. 2) was designed so that 7·6 cm. long core segments could be placed directly in a metal cylinder to prevent deflection. A load is then applied to special shearing heads that are positioned so as to align the shearing edges and produce a directed shear break across the axial plane of the specimen. As the load is applied, the force with time is recorded directly on a Varian recorder. The specimen shears across an axial plane of 58 cm.^{2}. The load during testing was applied at a rate of 20 cm./min., causing the ice to behave as a brittle elastic material.

It is recognized that friction and side loading in the metal cylinder may have a definite

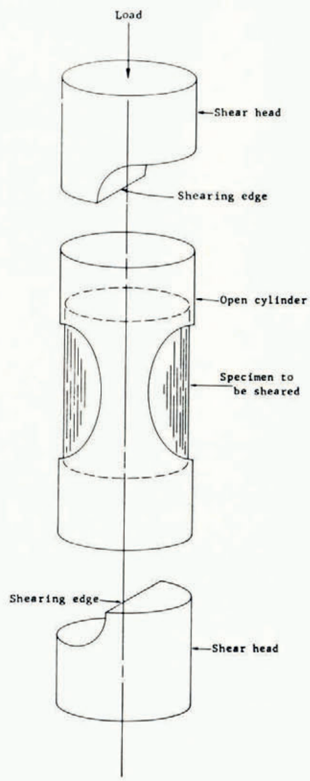

Fig. 2. Open cylinder shear apparatus

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effect on the shear-test results, especially in a cylinder that completely encloses the specimen and shear heads. A special open cylinder that has large parts of its wall machined out so as to reduce side loading and friction (Fig. 2) was therefore designed. The shear-test results as carried out with the open cylinder are approximately 2·5 times less than those in a closed cylinder. All shear-test results given in this paper were obtained with the open cylinder.

During the austral summer of 1964–65, the annual sea ice in McMurdo Sound was studied according to the following general plan. A series of five stations was established in a straight line between the end of the NCEL snow runway and Williams Field (Fig. 1). Periodic measurements of ice and snow thicknesses were made at each station throughout the season. Station No. 2 was arbitrarily considered to be representative of the sea-ice sheet for detailed studies of strength properties. Every 7 to 10 days, the ice at station No. 2 was tested for shear, ring-tensile strength, salinity and temperature. Because of the variations inherent in strength tests of small specimens of sea ice, two to four representative cores were tested. Separate cores were extracted for salinity and temperature measurements. Temperatures were measured with mercury-bulb thermometers placed in holes drilled in the core. Salinity was measured with a commercial conductivity bridge.

A series of 21 to 25 stations was located along the fuel line road from "The Gap" to Williams Field and over the shoal area off Cape Armitage (Fig. 1). Periodic measurements of ice thickness and snow depth were made at these stations in conjunction with strength studies to record the change of shear and ring-tensile strength with time and temperature. All stations were located by distance measurements and transit shots, and accurately plotted on a map.

Results

Strength

The strength of sea ice is controlled by several closely related and temperature-dependent properties such as salinity, size and spacing of brine layers and brine-drainage cavities, ratio of solid to dissolved salts, and ice-crystal size and orientation. Although it is recognized that the strength of sea ice is a function of brine volume, which in turn is a function of both salinity and temperature, the data in Figures 3 and 4 are based on brine-volume and temperature ranges of sea ice varying in salinity from 4 to 7 p.p.t.

The sea-ice sheet had a temperature difference across it of about 8·25° C. in October and it became nearly isothermal later in the season with a temperature difference of only 1·2° C. by late December (Fig. 5). The temperature difference across the sea-ice sheet has a strong effect on the average strength of the sea-ice sheet, because the cold ice near the surface is stronger than the warmer ice near the bottom, as shown in Figure 6.

Because the temperature at the bottom of the sea-ice sheet is essentially constant at the freezing point of sea-water, the surface temperature indicates the magnitude of the temperature difference that may exist across the sea-ice sheet and correlates well with changes in strength as illustrated in Figure 7. It can be seen that the shear and ring-tensile strength curves are nearly mirror images of the ice-surface temperature curve. It is also interesting to note that the shear strength reaches a low of about 5·8 kg./cm.^{2} in mid-January and then begins to increase just before break-up in mid-February.

Ring-tensile strength of sea ice is often correlated with brine volume which is a function of temperature and salinity (Assur, 1960, p. 7, 13; Langleben and Pounder, 1963, p. 75). Ring-tensile strength and shear strength versus the square root of brine volume is shown in Figure 8. The large amount of scatter in the data is common and it has been the subject of intensive research by Assur (1960), Graystone (1960), Weeks (1962), and Langleben and Pounder (1964).

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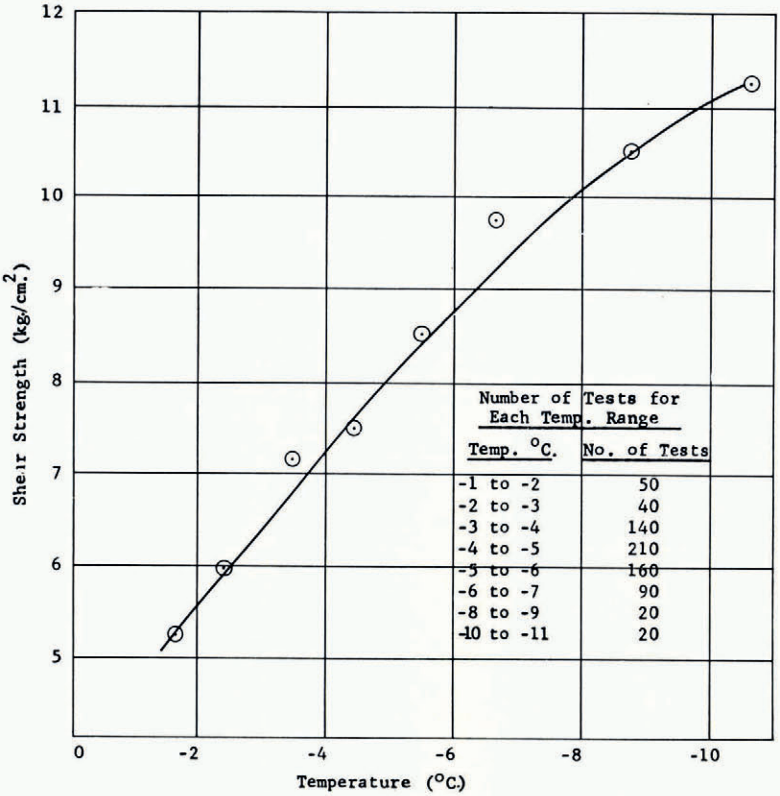

Fig. 3. Average shear strength of sea ice as a function of temperature. NCEL station No. 2

Thickness

The thickness of sea ice is directly related to the climate of an area and it is also controlled by the water temperature, currents, depth of water beneath the ice, snow cover and ablation during the summer. It is important that the general ice-thickness pattern as a function of time in any operational area be understood, because of its obvious value in determining the bearing capacity of the ice.

The sea ice in McMurdo Sound increases in thickness until late December. Bottom melting begins soon after and progresses rapidly until the ice breaks up in February (Fig. 10). The extent of break-out varies from year to year; however, it is likely that bottom melting occurs every year and is similar to that observed previous to 1965 (Hoffman and Stehle, 1963, p. 3; Stehle, 1963, p. 3; 1964, p. 3). Extensive bottom melting of the McMurdo Ice Shelf has been attributed to the temperature and circulation of water in McMurdo Sound (Stuart and Bull, 1963, p. 412). It is probable that bottom melting of the annual sea ice is also caused by the same factors. Even considering this bottom melting, it is quite apparent that the sea-ice thickness in McMurdo Sound during the period of most active use is sufficient (132–213 cm.; Figs. 9 and 11) for most operational purposes providing break-out does not occur.

The only known exception in McMurdo Sound is the shoal area off Cape Armitage (Fig. 10) where the ice becomes unusually thin late in the summer. In this area, a tractor broke through during the austral summer of 1964–65 and nearly cost the lives of two men.

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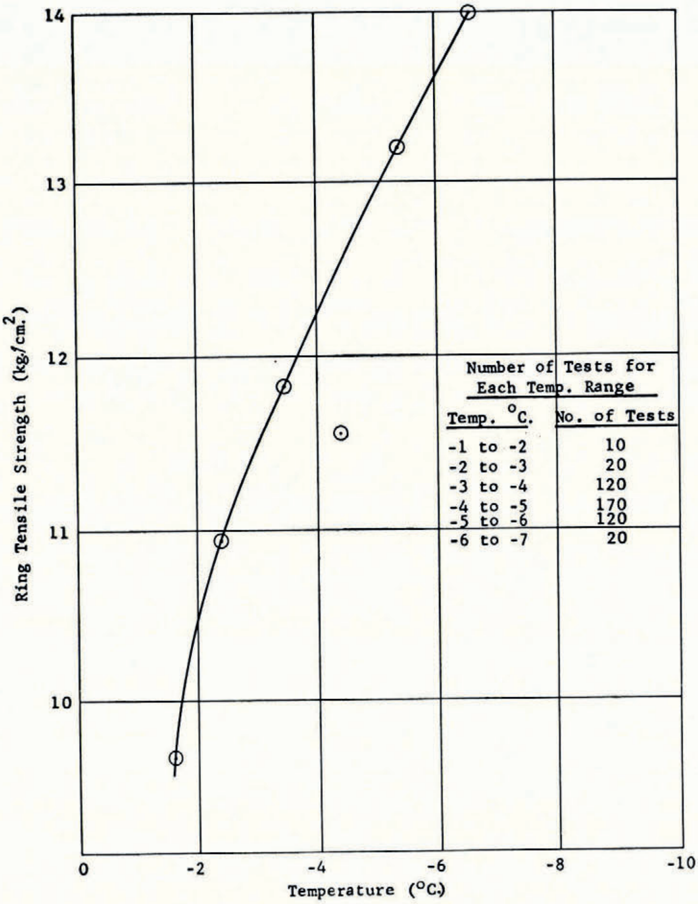

Fig. 4. Average ring-tensile strength of sea ice as a function of temperature. NCEL station No. 2

The area off Cape Armitage is about 364,000 m.^{2} in extent where the ice thins from 213–244 cm. early in the season to as little as 36 cm. by late summer as shown in Figure 11. Zubov (1945, p. 350) has described the occurrence of similar thinning behind or over shoals in Arctic regions.

Effect of snow cover

Snow covers much of the sea ice throughout the summer season and it varies in thickness from 2 to 60 cm. Even in areas blown free of snow, little evidence of surface melting is observed. It is well known that snow is an excellent insulating material and that its presence or absence has a definite effect on the ultimate thickness of sea ice (Zubov, 1945, p. 220). Sea-ice thickness can be increased by early removal of the snow cover (Assur, 1956, p. 13–14), although the removal of snow can also cause the formation of thermal tension cracks in the surface (Kingery and Coble, 1962, p. 65). Figure 12 shows the relation of ice thickness to snow cover. The trend is obvious in spite of the scatter which is probably due to erratic ice thicknesses.

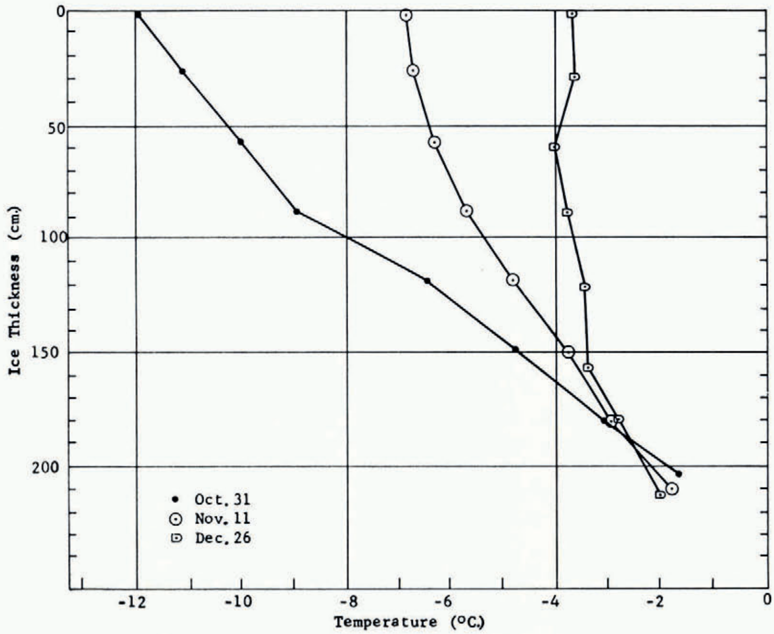

Fig. 5. Temperature difference across the sea-ice sheet on 31 October, 11 November and 26 December 1964

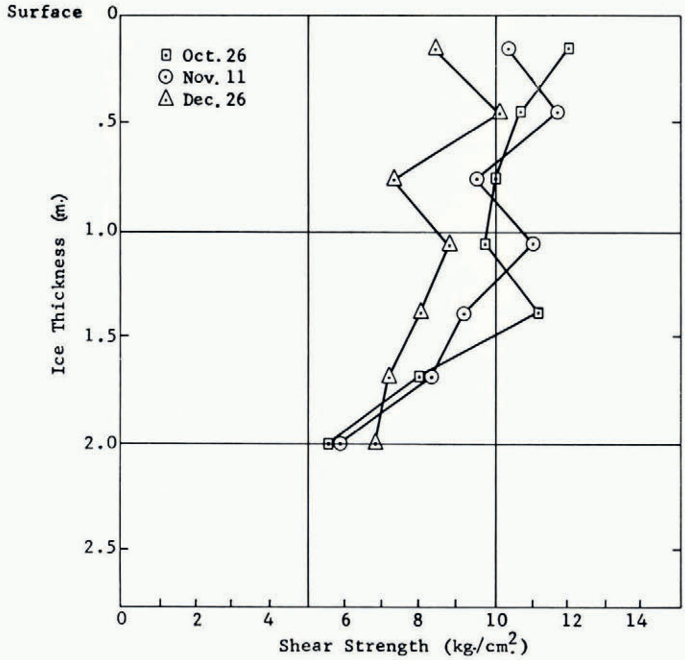

Fig. 6. Shear-strength profile of the sea-ice sheet on 26 October, 11 November and 26 December 1964

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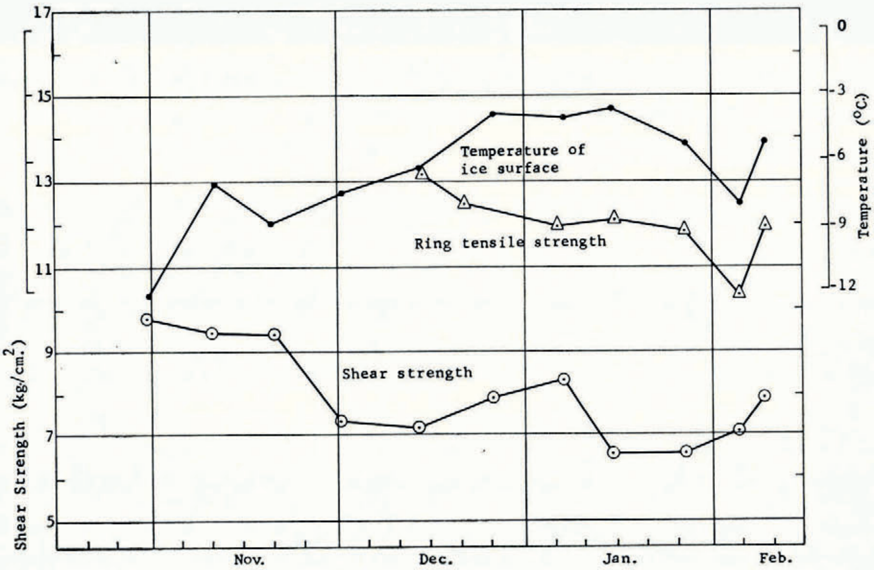

Fig. 7. Average shear and ring-tensile strengths of the sea-ice sheet compared with ice-surface temperature and time. NCEL station No. 2

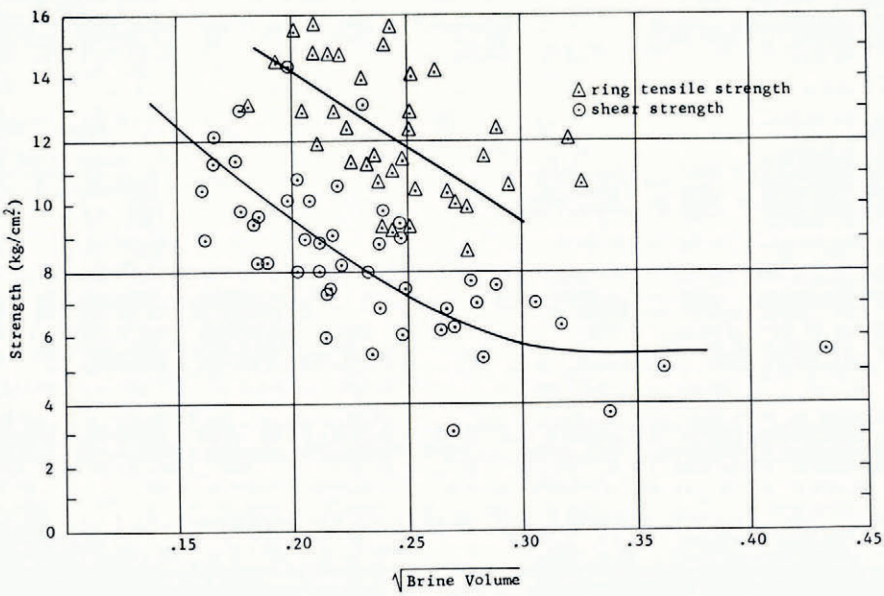

Fig. 8. Shear and ring-tensile strengths as a function of brine volume

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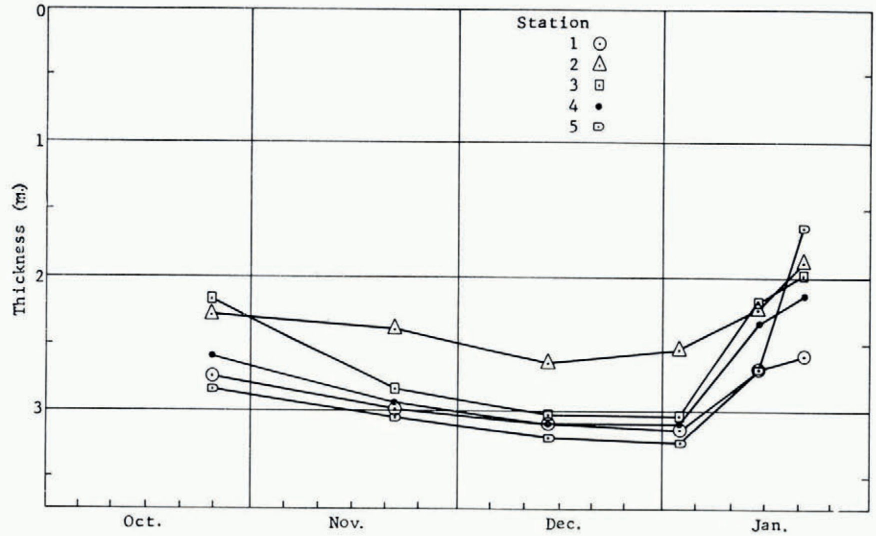

Fig. 9. Ice-thickness changes during the summer of "Deep Freeze 65". NCEL stations 1 to 5

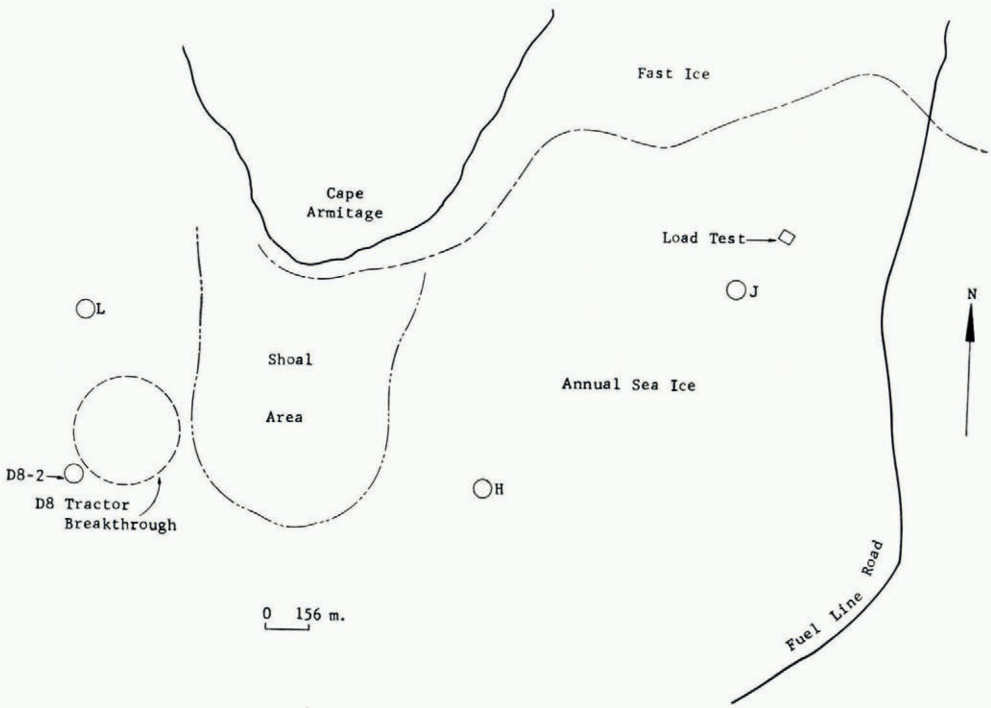

Fig. 10. Map of the Cape Armitage area

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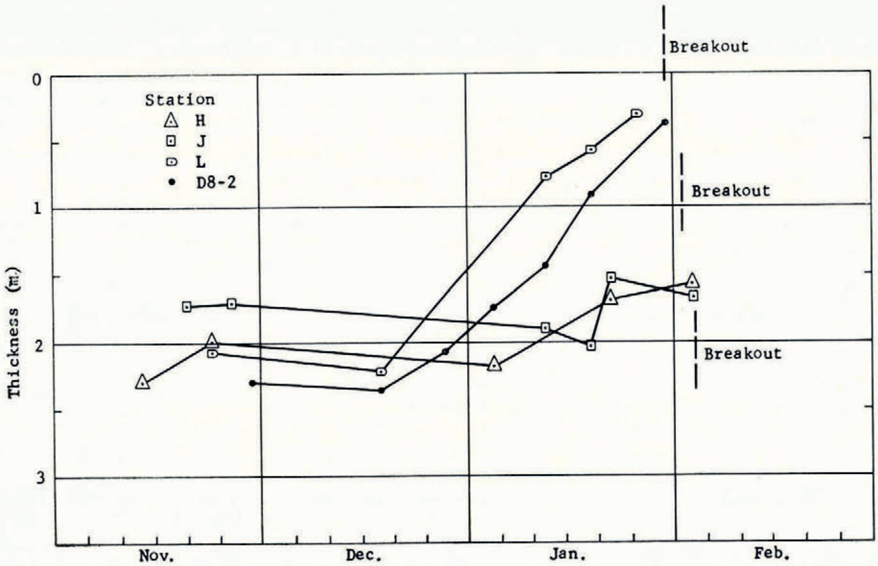

Fig. 11. Ice-thickness changes during the summer of "Deep Freeze 65". NCEL Cape Armitage stations D8-2, L, H and J

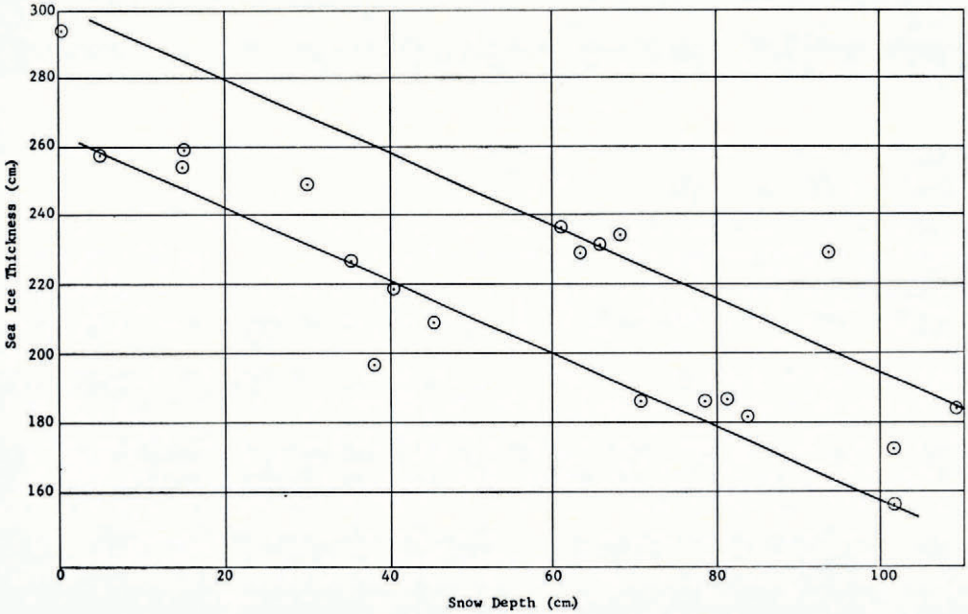

Fig. 12. Sea-ice thickness versus snow cover, December 1964

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Deterioration

Deterioration of the sea ice in McMurdo Sound is related to increasing temperatures and solar radiation during the summer and it occurs both internally and at the bottom of the sea-ice sheet. Only internal deterioration is of concern here and it is expressed by changes in the salinity, size and shape of brine-drainage cavities, and the progressive loss of shear and tensile strength.

Brown (1963, p. 80) has described the deterioration of Arctic sea ice and he has stated that "In the last stages of deterioration, the ice sheet becomes very granular and porous". Brine-drainage cavities (brine cells) in the ice of McMurdo Sound become progressively larger and interconnected during the summer, but the sea-ice sheet usually breaks up and goes out to sea before it approaches the stage of deterioration common for Arctic sea ice.

During the freezing of sea-water, brine is trapped in layers and cavities between platelets. The boundaries between the growing platelets form the initial brine cavities that enlarge, connect and drain by gravity as the ice becomes warmer (Kingery and Goodnow, 1963, p. 239). As brine drainage progresses, the salinity of the brine decreases with warmer temperatures as shown in Figure 13. This graph also illustrates the effects of temperature changes on the internal properties of the ice. Brown (1963, p. 86) has reported a decrease in brine content with an increase in temperature for Arctic sea ice.

As previously stated, solar radiation is an important factor in introducing heat into the sea-ice sheet and it has a definite influence on deterioration. The rate and amount of deterioration in the sea ice is controlled by the amount of snow cover. Figure 14 illustrates the effect of snow cover in protecting the sea ice from deterioration and loss of strength. This figure points out the advantage of maintaining a protective cover on sea-ice runways during the summer. The loss of strength is consistently less in ice that has been protected from solar radiation.

Cracks and seal holes

Cracks in sea ice and associated flooding of the surface often cause unwarranted concern, because of a lack of understanding of their true nature or a failure to investigate them. Sea

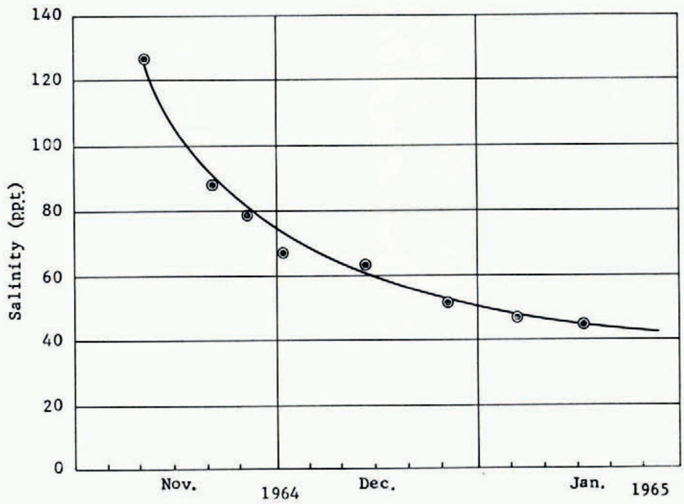

Fig. 13. Brine salinity versus time. Brine collected from core holes. NCEL station No. 2

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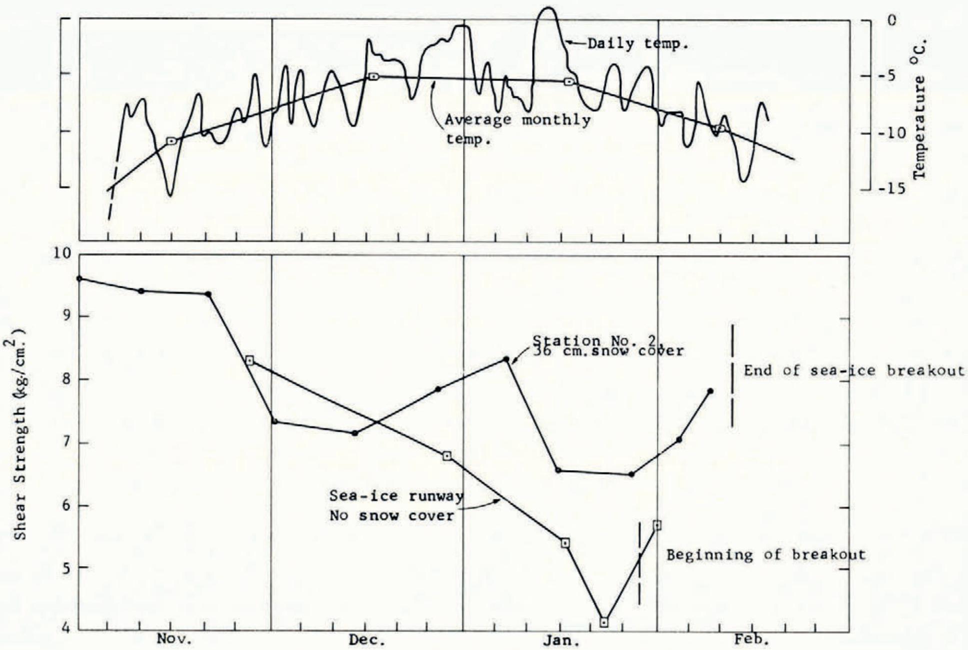

Fig. 14. Average shear strength of the sea-ice sheet compared with temperature and time

ice without some sort of crack pattern is exceedingly rare (Assur, 1956, p. 13) and, with the possible exception of an open wet crack near a load, the ice is "remarkably insensitive to the presence of cracks" (Kingery and Coble, 1962, p. 76).

Open wet cracks are those that completely penetrate the sea-ice sheet and tend to separate individual masses of ice. The load-bearing capacity of the sea-ice sheet in the vicinity of an open crack is that of an edge-loaded plate and is considerably reduced. An open crack does not necessarily penetrate entirely through the sea-ice sheet, especially during the summer when brine drainage is accelerated by high temperatures. Careful observation must determine if the ice on one side of the crack moves relative to that on the other side.

An open wet crack 34·6 cm. wide occurred in the annual sea-ice cross-wind runway and it was examined in detail in December 1964. A test of the water in the crack indicated a salinity of 44·6 p.p.t., whereas the natural sea-water had a salinity of 29·0 p.p.t. The difference in salinity alone is enough to show that the crack was not open to the sea below but it was partly filled with slightly diluted brine that had drained from the ice. Core drilling disclosed that the crack penetrated only 111 cm. in a sea-ice sheet 266 cm. thick.

Seal breathing holes are relatively rare early in the season and they occur only in pressure-ridge areas, near tidal cracks, or other areas of broken or disrupted ice. As the sea-ice sheet progressively thins during the summer, seal holes appear in greater numbers, but they are still restricted mostly to the thin-ice area off Cape Armitage and the pressure-ridge and tidal-crack areas south and east of Scott Base.

When a seal hole or open crack appears in snow-covered sea ice, the area around the opening is sometimes flooded with sea-water and the snow becomes slush. Flooding of the annual sea ice occurs frequently in the area east of Cape Armitage where the snow is often quite deep. Evidence of flooding is seldom visible because the zone of slush forms beneath a wind-packed crust of snow. Thickness measurements will usually indicate ice of sufficient thickness to support a considerable load. These flooded areas are, nevertheless, hazardous because heavy sled trains or other heavy vehicles can easily become immobilized if they break through the snow crust.

Conclusions

The problem of sea-ice strength is complex because of many influencing variables. Controlling factors within the sea-ice sheet are thickness, temperature, strength and degree of deterioration. Other factors include solar radiation, water temperature and currents, snow cover and tidal action.

Thickness is one of the important basic parameters affecting the bearing capacity of a sea-ice sheet. Numerous measurements during the austral summer of 1964–65 indicate that the thickness of the sea-ice sheet remains sufficient for most loads until mid-January.

It has been shown that the strength properties and thickness of the sea-ice sheet vary in response to ambient temperature trends, solar radiation intensity, the depth and circulation of water beneath the ice, and the amount of snow cover. Reliable prediction of sea-ice strength requires correlation of large-scale beam and static deflection tests with simple field tests and other criteria determined by continued study of all the various controlling factors.

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