PRELIMINARY REPORT ON LAKE PETERS, ALASKA
ICE STUDIES*

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Introduction

Aircraft operations on frozen arctic lakes are perhaps most common in the springtime when thin snow cover permits landings by wheel planes and summer field and construction programs are commencing. However, at this time of year the strength of an ice sheet begins to decay at a fairly rapid rate. Rate of this decay was studied in 1959 at the Lake Peters research station in northern Alaska by personnel of the U. S. Geological Survey and of Dartmouth College.

The Lake Peters investigation was an extension of previous Air Force Geophysics Research Directorate studies designed to determine the maximum period for use of frozen lakes as landing places for military aircraft. Previous work consisted of an intensive study which was made during the summer of 1957 of perennially frozen Angiussaq Lake, Greenland. Results of the Angiussaq work demonstrated the need for comparative studies of the rate of strength decay in ice that melts completely every summer. The establishment in 1958 of the Lake Peters research station and the planning of limnological and micrometeorological studies at this station for the following summer provided what appeared to be an ideal opportunity for further studies of melting ice during 1959.

The study began in late April, when the ice temperature was still slightly below freezing, and ended in late July when the ice became too weak to support equipment. The U. S. Geological Survey had originally planned to concentrate on measurements of thickness, elastic moduli, and ice strength, the three properties that determine the load-bearing capacity of a floating ice sheet. The program had to be expanded later to include many of the micrometeorological measurements which are necessary for determining the heat budget of melting ice. This added requirement somewhat limited the number of strength measurements that could be completed. However, a more serious limitation was imposed by the inaccessibility of Lake Peters, which caused long shipping delays and interruption of measurements.

Much of the field work was performed by Frank Leavitt of Dartmouth College, who is responsible for a large share of the success of the project. F. L. Riddell, the manager of the Lake Peters research station, was always cooperative and provided an especially valuable service in maintaining continuous electric power. J. E. Hobbie and E. B. Clark of the Arctic Institute of North America and Carroll Rock of the U. S. Army Quartermaster Research and Engineering Center provided the limnological and meteorological data. J. B. Lyons of Dartmouth College and

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Heat Budget Measurements

The rate at which the strength of an ice sheet decays varies greatly for different lakes and for different years. In 1959 Lake Peters maintained an ice cover until July 27, but the previous year all the ice had melted a month earlier. To provide a basis for applying ice-melt data to other lakes and other years, some measurements were made of the rate at which heat was being added to the ice sheet from the overlying air and underlying water. At Lake Peters a continuous record was maintained of the more important variables determining the rates of these heat transfers. The data were recorded on a standard 16-point, strip-chart recording potentiometer, which operated almost continually from May 9 to July 17, when the ice became too weak to support the equipment.

Most of the ice melt occurs at the top of an ice sheet as a result of convective heat transfer from the warmer air. Records of air-temperature gradient, air temperature, and wind velocity were maintained continuously to give an indication of the rate of heat transfer. An exact analysis of convective heat transfer would require additional measurements of humidity gradient and wind-velocity gradient, but equipment for such measurements was not available. Convective heat transfer over glaciers and sea ice has been studied by Hubley (1957) and Untersteiner and Badgley (1958). The results of their work are probably sufficiently applicable to lake ice to make an intensive study of air convection unnecessary.

Radiation balance is another factor that plays a major role in the melting at the top of an ice sheet. At Lake Peters a continuous record of incident solar radiation was maintained with a Kipp radiometer, which was inverted at frequent intervals during the day to obtain a measure of the surface albedo. Net long-wave radiation balance was recorded with a Beckman-Whitley radiometer placed about a meter above the ice sheet. Incident radiation and illumination were also recorded by a photocell, which was a duplicate of another cell placed directly below the ice sheet. These gave measurements of the amount of radiation that is absorbed within the ice sheet and the underlying water. Once the melting process begins, the temperature throughout the ice sheet is very close to the ice melting point. The thermal gradient within the ice sheet is very small or absent as little heat is transferred by conduction or convection. Heat can, however, be transferred by radiation, and absorption of radiation causes decay in the physical properties of the ice sheet in the middle and lower portions.

The radiation that penetrates the ice and is absorbed by the underlying water probably plays an important role in warming this water and in controlling the heat transfer and melting at the bottom of the ice sheet. Thermal conditions beneath the ice sheet were measured by the limnologist with a specially built thermistor probe. His data seem to agree very well with measurements of melting at the bottom of the ice sheet.

Late in the melting season several attempts were made to measure the total amount of radiative and other heat that had been absorbed by the ice in the lower part of the sheet. Most of this heat seems to go into melting at crystal boundaries and into the formation of Tyndall figures within the crystals. Therefore, the volume of water and vapor filled cavities within the ice should be an indication of the quantity of heat added to the ice during the whole melting season. However, no accurate method of measuring the volume of these cavities was found. A large number of photographs were taken and many rubbings were made of freshly sawed ice surfaces, but these do not give satisfactory measurements of cavity volume. Better results were obtained by measuring in a calorimeter the heat required to melt a small ice sample, but the small size of these samples prevented a representative sampling of the mass of the ice sheet. This measurement of volume of internal melting is very difficult, and better equipment should be designed and tested before additional field work is undertaken.

Ice Thickness

Ice thickness was measured every four days at nine places on Peters Lake, and surface ablation was measured daily at one station. Figure 1 shows the changes in ice thickness at three of these stations during the period May 19 to July 27. The decrease in thickness was considerably faster near the shore than in the center of the lake, but some of this difference is the result of a contrast in type of ice. The rate of melting increased throughout the summer except for minor variations caused by changes of weather. This increase is believed to be the result of a lowered albedo as the ice became thinner, of an increase in rate of melting at the bottom of the ice, and of progressively warmer air temperatures.

The rate of melting at the top of the ice sheet can probably be explained theoretically by application of the micrometeorological theories worked out for glacier ice, but the rate of melting at the bottom of the ice sheet had received little study before the initiation of the Lake Peters work. Measuring the melt at the bottom of the ice sheet is difficult because of the problem of marking a reference horizon within the ice. At Lake Peters, small squares of translucent white plastic were placed in the ice as reference markers. Early in the work most of these were attached to ablation poles and frozen into the ice, but all of the poles eventually melted loose. Another plastic sheet was attached to a thin white wire and placed in the ice, and this sheet could be used as reference marker until very late in the melting season. Results show that less than one-tenth of the ice melt occurred at the bottom of the ice sheet.

Elastic Modulus of Ice

The elastic modulus also influences the bearing capacity of an ice sheet, but this influence is not large, and the measurement of elastic properties did not constitute a major portion of the program. However, seismic velocities in the ice were measured several times during the season, and were used for the calculation of the elastic properties. The measurements were made along a thousand-foot geophone spread and recorded by a portable refraction seismograph. This instrument did not consistently record second arrivals, so the charge type and phone distance had to be varied to make the desired energy appear as a first arrival. Compressional waves were generated by small explosions fired in the ice, and shear waves by sledge hammer blows on the wall of a hole cut in the ice.

The first velocity measurements were made shortly after the middle of May, when internal melting of the ice had probably already begun. The longitudinal wave velocity at that time was between 11, 000 and 12, 000 fps indicating a Young's Modulus between 7 and 8 X 10^{10} dynes per cm^2. By early July the velocity had become so low that it could not be distinguished from that of the underlying water, and the elastic modulus was probably about 1 X 10^{10} dynes per cm^2. However, the ice still appeared to be capable of transmitting shear waves. Comparison of longitudinal and traverse wave velocities at the start and end of the melting season suggests a slight increase in Poisson's ratio as the melting progressed.

Ice Strength

Measurements of ice strength formed the major part of the Lake Peters research program. During the spring melting season the load-bearing capacity of an ice sheet usually depends more upon the decay in its resistance to tensile stress than it does upon the reduction in thickness. This is not the relationship that holds during the fall freeze-up when the increase in ice thickness plays the predominant role in increasing the bearing capacity of the ice. Ice strength may be measured in two quite different ways: (1) by breaking in a testing machine small specimens which have been cut and removed from the ice; (2) by using much greater loads to break large, in-place portions of the ice sheet.

About 200 small-specimen ice tests were made at Lake Peters. Ring-tensile tests as described by Butkovich (1956) were made on cylinders 3 inches in diameter, about 3 inches long, and each with a one-half inch diameter hole along its axis. Care was taken to prevent the formation of flaws during the cutting process. To reduce to a minimum the amount of heat that might be added to the specimen during its preparation, all specimens were broken within half an hour of the time they were removed from the ice. During this period they were kept as cold as possible and were shielded from solar radiation. Nevertheless, the test did not give a satisfactory indication of the strength of the melting ice sheet. Apparently, the effects of the melting process are concentrated at grain boundaries and distributed too unevenly through the ice sheet to be measured reproducibly in small specimens. As the melting progressed, the difficulty of cutting a satisfactory specimen increased tremendously, and the scatter of the results increased by an even larger amount. By mid-July the strength of the ice sheet as a whole had become very small, but it was still possible to obtain a few single-crystal specimens for ring-tensile tests. These single-crystals required nearly as high a breaking load as the strongest specimens tested before the melting began. The melting, single-crystal specimens gave lower strengths when their c-axes were oriented parallel to, and their Tyndall figures normal to, the direction of tension.

Large in-place beams probably give the best indication of the rate of decrease in ice strength because they sample a reasonably large portion of the ice sheet. The most common test of this type is the in-place cantilever beam, which has been frequently used for the study of ice strength (Neronov, 1946; Butkovich, 1956; Weeks and Anderson, 1958). A U-shaped cut is made in the ice sheet, and a load is applied at the base or free end of the U. On thick ice a load of several tons is required to break the beam, and at Peters Lake, as at Angiussaq in Greenland, this load was applied through hydraulic jacks working against toggles placed beneath the ice

(Barnes, 1958). Severe stress concentrations occur around the fixed end of the beam, so the measured strength values are 2 to 3 times lower than the actual strength of the ice. Nevertheless, the test does give comparative measurements of ice strength and is useful for measuring the decay in strength of relatively large samples of melting ice.

The first series of in-place cantilever beam tests at Peters Lake was made at about the time that the ice temperature first rose to the melting point. The results gave strength values very close to those obtained with beams of similar shape at Angiussaq. However, in Greenland the ice had been at the melting point for nearly two months so its rate of strength decay must have been very small. A second series of in-place beam tests was planned for ten days later, when the melting process was expected to be well advanced. However, while cutting the first beam of this second series the drive shaft of the large power chain saw broke. This accident delayed further testing for more than three weeks, and the difficulties involved in obtaining a replacement caused the postponement of many other important phases of the investigation.

When the replacement shaft reached the lake in early July, the ice was still nearly four feet thick; but its strength as measured by in-place beams had deteriorated to less than 1/10th of that obtained a month earlier. All of the breaks occurred at former thermal cracks which had once been refrozen and which had not appeared to influence the location of the earlier beam fractures. Accordingly, the strength decay is believed to be more rapid in the vicinity of refrozen cracks.

The last beam test made was on ice that had been shielded from solar radiation throughout the melting season by a cover consisting of a dark tarpaulin overlain by a white tarpaulin. At the time of the test the ice beneath this tarpaulin had about the same thickness as the rest of the lake ice, but it appeared much clearer and showed little evidence of internal melting. The beam test in July showed that its strength was almost the same as that measured in early May. This test is believed to be a good demonstration of the importance of solar radiation in causing the decay of physical properties within the ice; the tarpaulin had little influence on conduction and convection of heat which causes most of decrease in thickness.

The in-place beam test was originally chosen for the study of melting ice because it provided a large sample which could be cut and prepared without adding a significant amount of heat to the ice. At Angiussaq, where the water beneath the ice never rose above 0.4^{o}C, there was no evidence of significant heat addition. However, at Peters Lake the water beneath the ice had a temperature that ranged between 3 and 6^{o}C, and the lower part of the twelve-foot chain saw bar extended deep into this warm water. The saw acted as a very efficient pump and brought a large amount of this water to the ice surface. As this warm water percolated back through the ice it caused a noticeable amount of ice melt and decay. The effects of this warm water could probably be reduced in future work, but combined with the other fundamental limitations of in-place cantilever beams it seriously detracts from these tests as a measure of the strength of melting ice. The author believes that in the immediate future laboratory measurements on the ice would probably yield more reliable results.

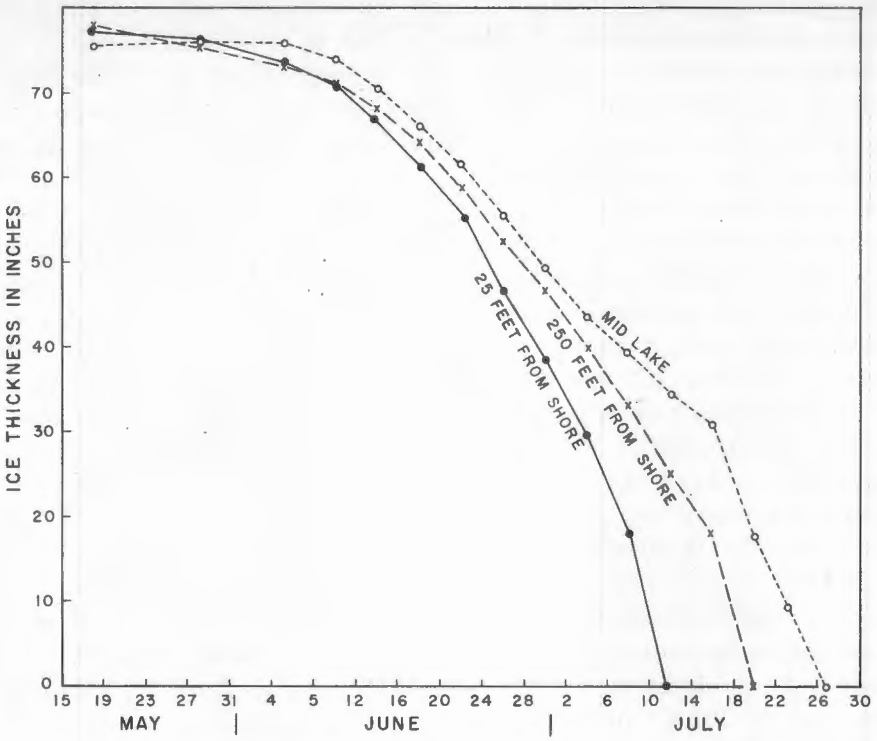

Fig. 1. Ice thickness vs date, Lake Peters, Alaska, 1959.

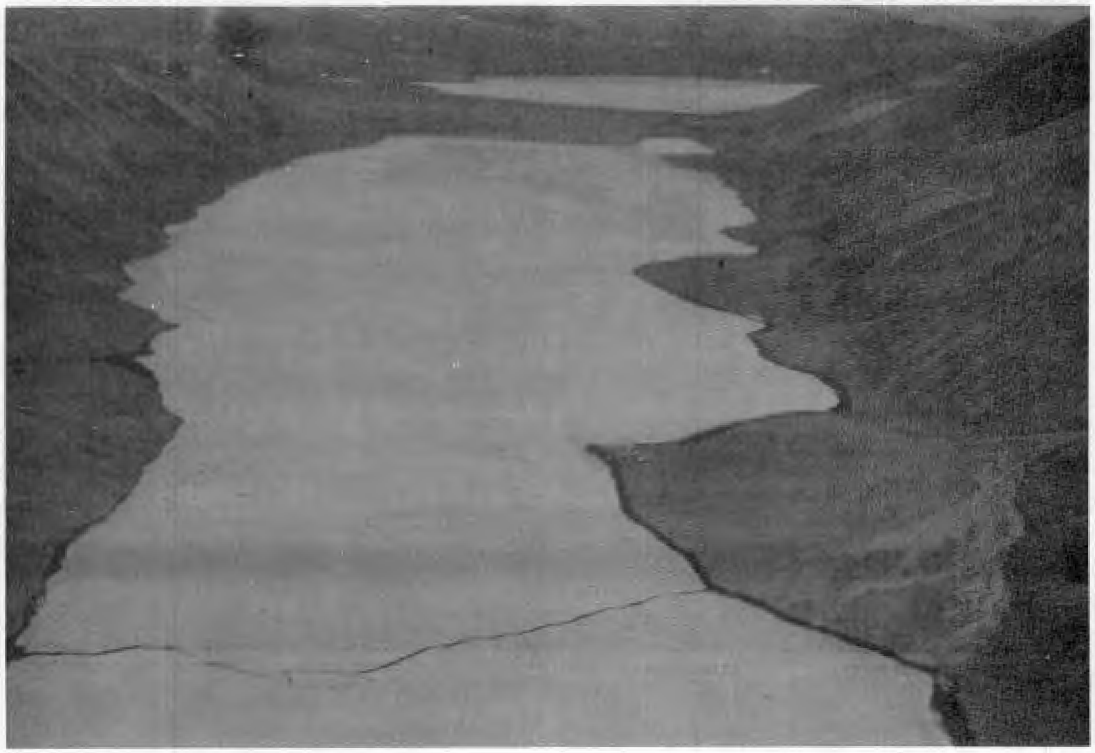

Fig. 2. Lake Peters, Alaska. Light areas represent the type of ice found at the test site. In darker areas all ice crystals appear to have horizontal c-axes.

One other test was made of the strength of melting ice, but its main result was that it did not show significant changes in the condition of the ice. The basis for the test was the frequently repeated suggestion that ice which has melted sufficiently will fail in shear rather than in tension. There is abundant observational evidence for this type of failure in thoroughly candled ice, and a measurement to determine whether shear failure would occur before flexural failure seemed desirable. Small-specimen measurements of double shear strength were planned, but shipping failures prevented arrival of the equipment before all the lake ice had melted. However, an in-place test was also devised and tried in the field. In this test the force required to punch a cylindrical or conical hole out of the bottom of the ice was measured. The load was applied by a metal punch 4 1/2 inches in diameter placed in a hole drilled to within 10 to 20 inches of the bottom of the ice. A load as high as 20 tons could be applied to this punch through a hydraulic jack, but the application required about a minute of pumping, and a large amount of plastic-yielding occurred before failure. Furthermore, examination of the blocks removed from the ice after failure showed that besides a shear cone punched out of the ice there were crack systems, which are believed to indicate some yielding by flexure and tension. The failure is thus influenced by high stress concentrations, plastic flow, and both shear and tension failures, so that interpretation of the test in terms of fundamental physical properties is unsatisfactory. The test is also limited in value. It is primarily a small specimen test with very large forces required and the load concentrated on a very small area.

However, the punch test did not show a very significant decrease in shear strength during the first two months of the melting season. In May the force required to punch through about 16 inches of ice varied between 20,000 and 40,000 pounds; in July 10,000 to 20,000 pounds were required to punch through ice of approximately the same thickness. The decrease in flexural strength during the same period was much greater. Extension of these results to larger loads and loading areas may be questionable, but until very late states of decay are reached, failures by flexure still seem more probable than failure by shear.

Structure of Ice

The primary purpose of the Lake Peters project was the study of the decay in ice strength as the melting season progressed. Studies of ice structures, crystal size, and crystal orientation were planned only as background information to make the data more easily comparable with data which might someday be obtained elsewhere. A small number of rubbings of etched ice surfaces were made in the vicinity of the test site, and some thin sections were also examined under polarized light. These show that at the ice surface the crystals were fairly large (measurable in inches) and that vertical c-axes predominated; however, horizontal c-axes became predominant in the lower third of the ice sheet, and average grain size also increased with depth. This general relationship held throughout most of the area in the vicinity of the test site.

As the melting progressed another type of ice covering about a third of the lake area was noticed. In the areal photograph, Figure 2, the two contrasting types of ice are noted. The lighter areas represent the type of ice found at the test site. In the darker areas all the ice crystals appeared to have horizontal c-axes, and the crystal size was probably somewhat smaller. The decrease in ice thickness and ice strength was considerably more rapid in the ice in which horizontal c-axes predominated. This difference was observed too late in the season to permit strength measurements on the ice with horizontal c-axes, but the qualitative relationship is clearly shown by the results in Table 1.

Table 1

DIFFERENCE BETWEEN ICE WITH HORIZONTAL AND VERTICAL C-AXES

	Predominantly vertical	Predominantly horizontal
Ice thickness May 15	73-77"	71-77"
Ice thickness July 1	48-52"	25-40"
Day melted completely	July 27	July 17
Last day supported man	July 26	July 10
Minimum thickness that could support a man	9"	20"

Conclusions and Recommendations

(1) Ice with predominantly vertical c-axes seems to maintain its strength and thickness longer than ice with predominantly horizontal c-axes. Continuation of investigations to determine the causes of these two types of ice is therefore recommended.

(2) Comparison of the results of similar in-place cantilever beam tests at Lake Peters, Alaska, and at perentially frozen Angiussaq Lake, Greenland, in 1957, show that the Angiussaq ice maintained considerably more strength.

(3) Solar radiation rather than heat conduction and convection appears to be the major cause of the decay in physical properties of melting ice. The effects of this decay are concentrated at refrozen cracks, crystal boundaries, and to a less extent at Tyndall figures within the crystals. Marked decays of both elastic constant and resistance to tensile stress were observed.

(4) None of the conventional field techniques of measuring the strength give satisfactory results for melting ice. A program of laboratory investigations is recommended before additional field work be attempted.

(5) No clear field criteria have been established for estimating how late in the season an ice landing strip may be used. Ice thickness measurements are useful but definitely do not provide all the necessary data. Perhaps measurement of seismic velocity is the simplest technique for estimating the amount of ice decay, although examination of ice cores by personnel with considerable ice experience may also give a good indication.

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