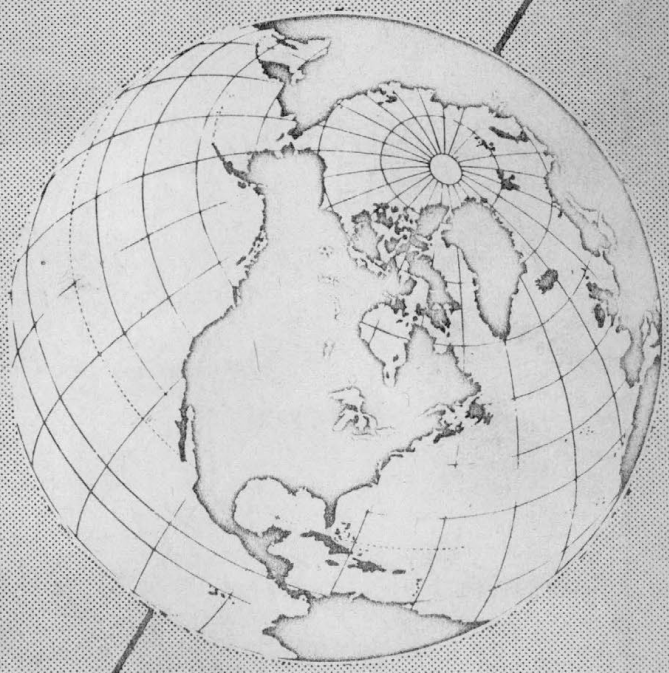
Sipre Report 36

PRELIMINARY EDITION
JANUARY, 1956

Airfields on Floating Ice Sheets

for Regular and Emergency Operations



SNOW, ICE AND PERMAFROST
RESEARCH ESTABLISHMENT
Corps of Engineers, U. S. Army

SIPRE Report 36

AIRFIELDS ON FLOATING ICE SHEETS
for Routine and Emergency Operations

by Andrew Assur

The following recommendations, covering only practical field aspects, are based on theoretical work, field experiments, and practical experience of personnel of the Snow Ice and Permafrost Research Establishment. They follow chronologically the procedures necessary for the establishment and maintenance of airfields on ice. This report was prepared by Dr. Assur under the direction of Mr. James A. Bender, Acting Chief, Snow and Ice Basic Research Branch.

SNOW ICE AND PERMAFROST RESEARCH ESTABLISHMENT
Corps of Engineers, U. S. Army
Wilmette, Illinois

AIRFIELDS ON FLOATING ICE SHEETS
for Routine and Emergency Operations

by
Andrew Assur

CONTENTS

1. General planning.

For preliminary considerations and long-term planning of operations on ice, it is necessary to have some estimate of expected ice thicknesses in a given region and at a given time of the year.

Usually no long-term ice-thickness observations will be available for a given theater of operations. Nevertheless the operational requirement will be to estimate whether and for how long it is feasible to land with a given type of aircraft on ice.

The thickness of ice can be related to the accumulated degree-days below freezing by the simple relation:

$$h_i = \alpha \times 1.06 \sqrt{S} \qquad (1)$$

which originally was developed for fresh water ice but can be applied also as a first approximation for sea ice.

h_i — ice thickness, inches.

α — coefficient, considering snow cover, stream flow and other local conditions. (See Table I)

S — accumulated degree-days since freeze-up, °F below freezing (32).

Daily mean temperatures are used. The date of freeze-up itself depends mainly on the size of the water body and the flow velocity.

Table I: Values of α (Equation 1) and β (Equation 3)

α	β	Conditions
1.00	3.6	Theoretically possible maximum, never reached under natural conditions
0.90 - 0.85	4.4 to 5.0	Maximum for ice not covered with snow
0.75 - 0.70	6.7 — 7.3	Arctic sea ice first approximation
0.75 - 0.65	6.7 to 9.0	Medium-sized lakes with a moderate snow cover
0.65 - 0.60	9 to 10	Bays with brackish water
0.60 - 0.50	10 to 15	Rivers with moderate flow

The values given in Table I are climatological averages. The variations from year to year are considerable, mainly due to changing

snow conditions. One can expect that, at a particular location, two-thirds of all individual α-values will lie within 25% of the average, but extremes from 60 to 160% of the average are possible. The variation for different localities is even more pronounced. Such an equation therefore can be used only for general and preliminary purposes and not as a substitute for ice surveys in the field for specific operations.

Methods are available for calculating the effect of stream-flow and snow cover, as well as for an efficient computation of degree-days from climatological data. They are not discussed here.

For a rough approximation S in equation 1 is based on the freezing point of fresh water. In a more detailed analysis the freezing point of sea water (around 29°F) can be used as a base temperature. More accurate and elaborate formulas for sea ice are available.

The growth of sea ice continues until the air temperature exceeds 10°F in the spring. Approximately at this temperature sea ice begins to diminish in thickness and strength. Limited information indicates that the ice thickness diminishes according to the relation:

$$\Delta h_i = \frac{S_{10}}{30} \qquad (2)$$

where S_{10} are the accumulated degree-days above 10°F.

Δh_i — reduction in ice thickness (inches)

Example: Cambridge Bay, NWT, Canadian Arctic. Long-term temperature curve crosses 32°F to lower temperatures on 13 Sept. Curve crosses 10°F line to higher temperatures in the spring on 8 May. Total accumulated degree-days below 32°F between these dates is 10,120. Equation (1) with $\alpha = 0.70$ gives $h_i = 75$ inches. This corresponds very closely to actual ice thicknesses measured at the beginning of May in a shallow protected bay.

After 8 May, on the average, the ice will decrease in thickness. The total accumulated degree-days above 10° on 15 June are 942. The expected decrease in ice thickness according to equation 2:

$$\Delta h_i = \frac{942}{30} = 31$$

and the expected ice thickness itself is 75-31 = 44 inches. The disintegration and weakening of the ice cover proceeds rapidly.

For an operation in a given year the estimates can be refind according to the actual preceding weather.

2. Principles of the bearing capacity of ice.

The bearing capacity of ice is not based on the fact that the ice

is lighter than water, as is frequently assumed, but on the resistance to bending under load. The curvature of bending of the ice surface is based on such parameters as Young's modulus, Poisson's ratio, the ice thickness, the pressure of the water against the ice cover as soon as a deflection develops and, last but not least, the configuration and concentration of the load. For instance, a man walking on a ladder placed on ice will be safe where a child broke through.

Young's modulus of elasticity is a force in pounds per square inch divided by the relative deformation in the direction of its application (within certain limits). Poisson's ratio is the ratio of the deformation perpendicular to the direction of the applied force and the deformation in the direction of the applied force.

The theory shows that the deflection of an ice sheet under load is quite limited in its horizontal extension. At a distance four times the "action radius", ℓ, (more exactly 3.92), a length which depends mainly on the ice thickness but has no relation to the magnitude of the load itself, the deflection of the ice cover becomes zero; at 5ℓ (or more precisely 4.94ℓ), the so-called "influence radius", a small upheaval of the ice cover occurs, and beyond 7ℓ the deformation becomes very small.

Since these distances are important for practical purposes, Table II shows the distance, $L = 4.94\ell$, at which an upheaval occurs. This distance has to be considered in resonance waves. For safe distances between loads, 4ℓ, or 20% less than the values given in Table II, can be used. These distances are computed for normal ice conditions and slowly moving loads. Static (parked) loads have a smaller influence radius, especially on weaker snow ice. Faster moving loads on cold ice might produce higher radii.

The distances given in Table II are not very critical, and can be somewhat reduced if necessary.

Table II. Radius of influence of loads on floating ice

Ice thickness (in)	Basic load-influence radius, $L = 4.94\ell$, (ft) Fresh water ice	Sea ice
10	90	80
15	120	110
20	150	140
25	180	160
30	200	180
35	230	210
40	250	230
45	270	250
50	300	270
60	340	310
70	380	350
80	420	380
90	460	410
100	500	450

The ice cover has a certain resistance to bending, depending on its thickness and its flexural strength, which can be measured in the field by fairly simple tests. The first cracking occurs under tension on the bottom. This first cracking was long regarded as a criterion for safe use of ice and a safety factor of at least 2 was usually applied against this first cracking. In many cases operations would be made impossible by such requirements. Large-scale field tests performed by SIPRE have shown that loading may substantially exceed the first-crack limit without causing a final failure of the ice sheet. Cracked ice usually heals itself overnight.

The reader can convince himself of the additional reserves in bearing capacity beyond first cracking by making a simple test, without any special equipment, which illustrates some important features of the mechanical behaviour of an ice plate.

Take an ice sheet 1 $^1/_2$ - 2" thick and place it on the ground on a few supports. A small stone dropped on it will shatter the sheet into hundreds of pieces. It will certainly not hold your weight if you stand on it.

Now step on an ice sheet of the same thickness (transparent ice is assumed), supported by water. It might crack loudly under your weight, expecially upon a slight impact, but you won't break through. Stand with three other people close together (water must be shallow). The ice will crack considerably more and sag noticeably under this weight, but in most cases your feet will stay dry if the test is of short duration (a few seconds). If you stand longer, you will finally break through.

Such a simple test provides some basic information:

a) First cracking should not lead to concern.

b) There is ample warning before the ice fails.

c) The bearing capacity of ice is substantially higher than the load producing the first crack.

d) Prolonged application of a load produces failure, quick loading or moving around reduces the danger.

e) If noticeable sagging is observed, the load should be removed.

SIPRE is continuing with large-scale loading tests in the field by more elaborate and detailed methods, but the results are similar to the simple conclusions drawn above, except that exact figures and numerical criteria are derived.

In particular it was found that the bearing capacity depends also on the flexural strength of the ice cover with tension in the top layer,

subject to ice and weather conditions. A factor was introduced, which is governed by the military risk, resulting in criteria for regular and emergency use of an ice cover.

It can be shown that the few parameters mentioned above can be combined with the mathematical solution obtained by use of theoretical mechanics to predict the bearing capacity of ice for any particular vehicle or aircraft and for varying ice and weather conditions. Of course, adequate safety factors are introduced in all computations. Some results are given in Appendix I.

Experience during the Second World War has shown that resonance waves produced in the ice cover may cause accidents. Trucks moving in formation broke through the ice where all previous experience indicated complete safety. New studies have been made of such waves, and also of their magnitude and laws of generation (see SIPRE Report 34*).

On shallow water, the critical velocity of moving loads depends mainly on the water depth and, to some extent, on the thickness of the ice. In the case of an aircraft, the major concern is with taxiing, which proceeds at a velocity of about 18-20 mph. Easily visible resonance waves produced by taxiing aircraft have been reported by foreign observers. Ice thickness was marginal and the aircraft finally broke through. The critical depth for the occurrence of such velocities is about 20 ft, as shown by Table III.

Table III. Critical velocity of moving loads on ice over shallow water of a given depth*

Water depth (ft)	4	6	8	10	15	20	30
Critical velocity (mph)	9	11	12	14	17	19	22

*Approximate values are given. Exact values depend on ice thickness also.

While the aircraft is slowing down on shallow water, high velocities are irrelevant, and actually cause smaller deflections than a parked aircraft.

On very deep water, the critical resonance velocity depends only on the ice thickness (Table IV).

In this case (for example, aircraft on pack ice or frozen leads over deep water), critical velocities are relatively high, and it is easy to taxi at lesser velocity.

Safety factors against resonance waves are provided in our computations. In selecting an airfield, however, proper attention

* Wilson, James T. (1955) Coupling between moving loads and flexural waves in floating ice sheets, Report 34, Snow Ice and Permafrost Research Establishment, Corps of Engineers, U. S. Army.

Table IV. Critical velocity of moving loads over ice on "deep" water

Ice thickness (ft)	Critical velocity (mph)	Minimum depth which can be considered as "deep" (ft)
0.5	19	40
1	23	60
2	31	100
3	37	140
4	41	180
6	48	290
8	53	410

should be given to the best location in relation to the shoreline, as explained below.

Extensive operations on ice should not be undertaken without a careful ice survey by specially trained and qualified personnel. Men with initiative and an adequate sense of responsibility for both safety and efficiency of the operation should be selected for such assignments. In special cases such as the use of a railroad or the landing of heavy aircraft on ice of doubtful safety, additional rather simple mechanical tests to determine the ice strength are necessary.

3. Preliminary choice of location of airstrip.

This choice is done on the basis of maps (scale at least 1:500,000) or aerial photographs.

When operating on minimum ice thickness, the width of the water body, lake or bay, should be at least four times the load-influence radius, L (Table II). The runway has to be located at least 2L from the shore in order to avoid unfavorable reflection of resonance waves, especially in shallow water. This requirement eliminates narrow water bodies, except under conditions of emergency or great ice thickness.

Fresh-water ice: Medium-size lakes are desirable. Large lakes are subject to excessive thermal contraction and expansion of the ice cover as well as to wind action, which causes leads even in thick ice covers during the winter (example Great Slave Lake in Northwest Territories, Canada). Large lakes usually have smaller bays suitable for runways.

Landing of aircraft on rivers is feasible, especially if the width of the river is substantially less than the resonance width 2L. (Table II). Aerial photographs of the river will help considerably in choosing prospective places. The configuration of the river course gives clues to the location of the fastest currents where the

ice is thinner. Flooding, especially dangerous if a double ice layer is formed, can be detected by photography with suitable filters, which bring out the yellowish color. Desirable places are dead arms of a river or ox-bow lakes which are formed by cut-off parts of a meandering river, a very frequent occurrence in the sub-arctic.

Sea ice: Select location in a bay or behind a point of land so that airfield will not be subject to horizontal pressure, which causes extensive cracking. Unprotected airfields might be carried away by currents. In the absence of any data on currents, assume that the direction of coastal currents, looking from the land, is usually to the right in the Arctic and to the left in the Antarctic. Shelf ice also forms protected bays in many cases. A shelf-ice bay has the added advantage that, during summer, ships can sometimes unload equipment directly on the sea ice remaining in the bay, and an air-strip can be established here also.

Active cracks (with ice movement in vertical and horizontal direction) usually develop from points of land, in the direction of the current and towards the coast. Bays are usually separated from the ice cover in the open sea by such an active crack. Anticipate such cracks and choose a bay long enough to avoid them.

The open sea is usually covered with pack ice, either frozen solidly together or with constant formation of leads, depending on time of year, weather conditions, and geographical location. For example, Hudson Strait, Foxe Basin, and Gulf of Boothia are covered with drifting pack ice with leads even during deep winter, while oversea tractor transportation is possible west of Boothia peninsula.

Accumulated experience over many years has shown that it is completely feasible to operate on the pack ice of the open Arctic Ocean (Russian expeditions).

The limiting factor on pack ice is normally not its bearing capacity but the distances between pressure ridges. Ice fields with a diameter of about 1 mile can be found quite frequently, larger ones with increasing difficulty. Aerial photography can show the frequency of ice fields of necessary size in a given region. The takeoff run for different aircraft is given in Appendix I.

The actual inspection of ice conditions in the field has to be done by trained personnel. Research on airborne indicators of ice thickness and strength is under way, but equipment and criteria are not yet available.

4. Exploratory field survey, for check of ice conditions and final location of sites.

Use light aircraft for safe landing. Ice thickness, estimated from degree-days, should be up to twice the thickness required for the reconnaissance aircraft.

Circle above proposed site several times. Make sketch of coastal configuration, approaches, location of rafted ice, cracks etc.

Aerial inspection must be done from a higher elevation to get a general view of the area and from a lower altitude for details. Observation from the pilot's cockpit offers some advantages. Snow drifts give some idea of the frequency of different wind directions and the prevailing wind, especially if combined with knowledge of the general air circulation.

Some regions have excessive tides causing hummocking, rafted ice etc. The probability of high tides can be anticipated from the general configuration of the sea, but experienced observers will soon find that they can estimate the intensity of such tides from the air, observing the ice formations along the coast. In regions of high tides, narrow places on the end of bays and between islands are points of increased danger. In many cases the water never freezes here due to the presence and constant change of currents, or if it freezes the ice will be thin, dangerous even for light aircraft.

Make a landing and decide on approximate location of air strip. The problem of adequate approaches, which always enters the survey at this phase, is not discussed here. Consult pilot on adequate approach and length of runway. One warning might be added. Never, except in emergency, locate an airstrip closely parallel to shore with high bluffs, with the runway perpendicular to the prevailing wind. The local circulation pattern endangers smaller aircraft and causes trouble even for the heavier ones, especially if the ice is smooth and slippery.

Fresh-water lakes usually have a very smooth ice surface. The wind often keeps wide areas bare of snow. Construction workers tend to select these bare areas for airstrips in order to avoid snow removal, but judgment has to be used if the surrounding terrain is hilly. These bare areas often are a fairly reliable indication of an undesirable local circulation pattern.

As far as ice is concerned, the worst possible location is parallel to shore at the basic load-influence distance (Table II) and with a water depth of some 20 ft. Under these conditions, a maximum wave resonance effect will result when taxiing at 20 mph. Avoid such a location if at all possible. This holds for minimum ice thicknesses. On thicker ice, resonance oscillations are less dangerous.

The best location is an airstrip with an angle of at least 45° to the shore and nowhere closer to shore or shelf ice than twice the load-influence distance. In many cases it will be difficult to find such an optimum location. Another solution, especially applicable for ice of doubtful safety, is to land on the water-supported ice and run out onto land-supported ice. A very careful ice survey is necessary in this case. The land-supported ice is bound to be or become rough, causing increased stresses in the landing gear. A tidal crack will usually be found or develop across the airfield between the water- and land-supported ice. There is

also always the danger of failure due to air pockets under the ice, even with smaller loads.

The same holds for shallow lakes, partly frozen to the bottom. The resulting surface might be intolerably rough and uneven. A shallow lake may be fairly smooth during the ice survey, but become very rough later when the ice reaches bottom, or cracks and deforms after several landings.

Check ice thicknesses over the runway and especially on prospective parking areas. A minimum of four holes should be made if ice thickness substantially exceeds requirements, one in each of the two parking areas and two on the runway. One of the runway holes should be made a little ahead of the place of touchdown, the other at the place of propeller reversal. If ice is close to minimum thickness, make more holes to ensure that there are no thin areas, particularly under large snow drifts, over shallow water, and near points of land. Be careful in measuring the ice thickness; careless and unreliable measurements are made more often than one would suspect.

Note average and maximum thickness of snow covering the ice. Measure ice surface temperature under the snow cover.

Make a reconnaissance on foot, sketching location of cracks over $^1/_2$ inch wide. Note whether crack is dry or wet; record its width.

Sea ice might be formed from chunks of ice frozen together. Pilots do not appreciate the resulting roughness. Select places with a smooth surface. Holes kept open by seals throughout the winter are a rather remote but nevertheless real hazard. They might be covered only slightly by snow. No seals are to be expected in regions completely frozen over. In regions with constant formation of leads, seals live in the leads and don't bother to keep ice holes open. It is in the marginal zone between such areas that some precaution is recommended. Eskimos with dogs will be quite efficient in locating such holes ("nechik putogonane", in Canadian Eskimo, means "Where is a seal hole?").

Fresh-water lakes might have thin spots due to the presence of underwater springs. In regions with oil formations, natural gas, rising from the bottom, might form weak porous ice. Accidents due to this cause have happened.

Ice on rivers is the least reliable. Thickness may change over a very short distance. The thinnest ice will be found on shallow water with strong currents. Rotten ice is often found under deep snow drifts in well protected places.

It is not recommended, in general, to locate the airfield on ice subject to horizontal movement. Such movement is sometimes indicated by rupture points, which are slight elevations of four corners formed by intersecting cracks. Eventually these corners are raised by horizontal pressure up to 10 feet, causing peculiar

formations. The original location of the two distinct crossing cracks can always be found. Another type of hummock is formed by pieces of ice stranded on a shallow place. These are even higher and wider formations and may consist of ice several years old. Such hummocks are not a sign of horizontal pressure. Excellent airfields sometimes can be established on deeper water behind a line of ice stranded on a reef.

Wide leads with open steaming water are a common occurrence in some parts of the Arctic. They open and close depending on the direction of the wind. Yet, locations with excellent firm ice can be found nearby. It is readily conceded that it seems dangerous to fly over the steaming water and land on the edge of an ice cover. There is no reason for concern, however, if the reconnaissance party did a good job in the layout of the airstrip. The runway will be far enough from the edge and well protected, but the ground party should provide the pilot with special information on the presence and direction of leads.

Steaming water might impair visibility locally. Usually the wall of fog rises around 11 am, increasing in intensity and then decreasing again towards the evening. The morning hours will give the best visibility.

Decide on proper location of parking areas with a minimum number of cracks. At least two parking and unloading areas for alternate use are recommended. If frequent cracking is expected, two alternate airstrips might be necessary.

5. Special considerations for emergency airfields.

Here we mean the use of ice which is barely thick enough to support the weight of the aircraft to be landed. These minimum ice thicknesses are listed under "Emergency" in the table, Appendix I.

It is self evident that an especially careful ice survey has to be made. Landings will frequently crack the ice cover, so that alternate runways are required to let the ice heal. The distance between the two runways should be at least 2 $^1/_2$ times the load-influence distance (Table II) if located on shallow water (around 20 ft). It can be diminished to the single influence distance on deep water with ice thicker than 20 inches.

In some cases it might be desirable to have an emergency ice airfield near a permanent airbase in order to save the crew when trouble develops during or soon after take-off.

The recommended procedure is to make a survey of ice thicknesses over the whole area at frequent intervals, while the ice is still reasonably thin. A special fast-drilling SIPRE ice auger and an ice-thickness measuring device can be provided for this purpose. Prepare a map with the configuration of the shoreline and with isolines of ice thicknesses in order to detect weak places, which usually occur every winter at the same locations.

Draw areas on this map within which the alternate runways could be located, considering approach and other related conditions. Prepare a similar map showing the depth of the water. This map will help to evaluate wave resonance conditions, which must be considered on marginal ice.

6. Decision on suitability of ice cover for an airstrip.

Appendix I, with attached remarks, gives ice thicknesses required for regular and emergency use of selected aircraft depending on weight, temperature, cracks, type of ice, and duration of parking. On this basis the final decision on the suitability of a certain site for a particular aircraft can be made. Some judgment is necessary to apply these criteria and to distinguish between important and less vital ones.

The bearing capacity of an ice sheet not only depends on the ice thickness and type, but also on the prevailing temperature. Ice temperatures adjust slowly to changes in weather conditions so that daily air temperatures, averaged over a number of days, should be known for best use of the ice thickness tables.

It will be noticed that ice thicknesses for regular operation at low temperatures are similar to those for emergency operation at temperatures near the melting point.

It is feasible to operate with reduced loads if ice conditions are marginal. Such conditions might arise, for example, if the pack ice field with the runway splits under horizontal forces and takeoff has to be attempted on a neighboring newly frozen lead. Practical experience has shown that it is possible to save the aircraft in this case by removing the load and less important equipment. The ice and runway requirements can then be considerably reduced. Criteria for reduction of required ice thicknesses in case of reduced load are given in Appendix I. If under exceptional circumstances normal grossweight is exceeded, the required ice thickness has to be correspondingly increased.

Although parking under specified conditions is allowed for a certain length of time, the behavior of the ice cover under the aircraft should be watched. If sagging is visible the aircraft should be moved.

If an engineering level is available, the deflection of the ice cover can be observed by means of a rod placed near the aircraft directly on the ice. No danger at all is present if readings are constant. Special attention is required if readings increase at a uniform rate. Immediate moving or removal of aircraft is necessary if readings increase at an accelerated rate.

Test landings may have to precede regular use if operation beyond accumulated experience is necessary. The pilot must remain in his seat, ready to move the aircraft at a signal from the ground observer.

Although aircraft have run successfully on slush surfaces, regular operations should cease as soon as slush conditions are encountered. Slush thrown against control surfaces and into the wheel wells sometimes freezes after take-off, creating a hazard.

Slush usually forms in the spring from melting snow. Such conditions, with the possibility of a hard crust and double layers of ice after refreezing, can be detected from the air: grayish spots appear on the usually white surface.

In milder regions with abundant snowfall, slush can form at any time during the winter also. The condition is that the weight of the snow cover depresses the ice until water seeps up through cracks into the snow, producing slush. Such bleeding cracks can be seen from the air. It is a rule of thumb to begin looking for slush formation when the depth of the snow layer approaches $^1/_3$ of the ice thickness.

Slush and double layers of ice also form quite frequently on rivers owing to changes in water level.

Slush sometimes refreezes to form so-called "snow-ice", which is full of air bubbles and much weaker than clear ice, Appendix I gives instructions for discounting snow-ice.

Guiding criteria are also provided for evaluating cracked ice fields. The existence of cracks, old or new, often leads to unjustified concern. Uncracked ice is rare. Operations on cracked or cracking ice can be quite safe if it is sufficiently thick and under close observation and maintenance (healing of open cracks with slush).

Theoretical considerations show that a cracked ice sheet can still support an appreciable load. Actually it takes a much larger load to produce a second crack than a first. In addition ice might crack without load or with a small load, owing to temperature-induced stresses.

7. Establishment and maintenance of airstrips.

Immediate snow removal is mandatory if the bearing capacity of the ice cover has to be increased. Making an early survey for the location of the ice runway and clearing the snow well in advance of the planned operation will result in thicker and stronger ice. The success of an operation might depend on early action.

Snow removal is often necessary for landing on wheels. Even for ski-equipped aircraft, it is desirable to level larger snowdrifts or to select a smooth area. Bush pilots have crossed open cracks up to 10 inches wide, but landing parallel to wide cracks is dangerous, even when they are frozen (formation of deep ruts).

Snow removal is best done by special equipment, which can be airdropped. If it is not available, nothing smaller than a D-4 tractor should be used. The wind-packed Arctic snow is extremely hard.

A tractor is not very efficient for snow removal, but convenient if it has to be used for other jobs also.

It is true that wheeled aircraft, such as the C-46, C-47, C-119, York, Lancaster and Bristol have landed on unprepared or manually prepared surfaces on the DEWline. But these were emergency cases, mostly for the delivery of tractors for snow clearance. Although there were no accidents, such landings were considered hazardous. Wheeled aircraft should generally not land in snow deeper than $^1/_3$ of the wheel diameter. Snow-removal tractors (disassembled) were also delivered by ski-equipped C-47's, or air-dropped (with some losses).

A 2-3 in. snow layer should be left on the ice for good braking action. Even ski-equipped aircraft can operate better on snow, because the sea-ice surface itself has high friction with skis, owing to its high salt content.

Sea ice is practically always covered with snow, even in the strongest wind, because of the relatively rough surface. A thaw, of course, can remove snow completely by melting. On refreezing, a surface much smoother than ordinary sea ice can be formed.

Fresh-water lakes usually have a very smooth ice surface, which, when swept bare of snow, offers very little grip to aircraft tires.

Aircraft have made hundreds of successful landings on smooth, slippery fresh-water ice by propeller reversal. But some accidents have happened to smaller aircraft which could not brake, and sheared landing gears in snow piles at the end of the runway.

If a more useful airstrip, especially for civilian use, has to be made on smooth fresh-water ice, it is advisable to soak a 2-in. snow layer by spraying with water. The frozen snow-ice layer gives excellent braking action and will hold subsequently falling snow.

A 2-3 in. snow layer left on top of the ice cover has the added advantage that rapid changes in air temperature are not immediately transmitted to the ice. Bare ice cracks easily on a rapid temperature change, as can be readily observed on all windswept lakes. The same temperature change, if slow, is less likely to crack the ice because stresses can be relieved by plastic flow.

On the other hand the snow cover acts as an insulating blanket, considerably retarding ice growth and reducing its strength. The insulating effect of a snow cover, expressed in terms of an equivalent ice thickness, is shown in Table V.

Table V illustrates strikingly why immediate and continuous snow removal and compaction of the remaining 2-3 in. layer is necessary for development of greater ice thickness and strength.

Table V. Thermal insulating effects of different types of snow on ice cover.

Type of snow	Normal density, γ_s	Equivalent ice layer, having the same insulating effect as 1 in. of snow cover, r
Freshly fallen snow	0.10 - 0.12	75 - 52
Slightly settled snow	0.14 - 0.18	38 - 23
Normal snow cover	0.20 - 0.25	19 - 12
Old snow	0.25 - 0.30	12 - 8.3
Hard-packed snow-drifts in the Arctic	0.35 - 0.40	6.1 - 4.7
Windswept snow cover during extreme cold (arctic)	0.40 - 0.45	4.7 - 3.7
Artificially compacted snow	0.45 - 0.52	3.7 - 2.8

Note: Snow cannot be compacted much above 0.5 density without considerable effort.

A 2-3 in. compacted snow layer, corresponding to an equivalent ice layer of about 6 inches does not seriously retard the strengthening of the ice cover, yet will tend to conserve the bearing capacity in the spring by retarding the effect of higher air temperatures and delaying ice deterioration. Loose snow must be removed when thawing starts or it will slush.

Snow piles on the sides of runways weaken the ice underneath and form relatively deep ditches by slow plastic yielding. These piles aid in orientation during landing but should be leveled out if higher than some 3 feet, or $^2/_3$ of the ice thickness, whichever is larger.

No, repeat no snow piles are permissible at the ends of the runways. It is important to enforce this rule rigidly in order to minimize accidents in case of short or long landings. Most of the few accidents on the DEWline were aggravated by failure to follow instructions regarding snow piles.

Because of the poor visibility of features on a snow-covered ground, the runway must be properly marked. Arctic white-out, due to the uniform radiation properties of the whole landscape and sky under overcast conditions, causes loss of contrast. Large orange panels lined up perpendicular to the sides of the runway are recommended for indicating the point of touchdown. Addition of a short line of fuel drums is a desirable accentuation.

Allow for an adequate overrun at the ends of the runway. The sides can be marked by empty fuel drums not more than 300 feet apart. Place no solid markers across the runway at the ends. A semi-permanent airfield on ice may need adequate lighting markers for night landings.

Always keep an empty drum filled with kerosine-soaked dirt or rags (or a smoke bomb) about 1 mi. from the head of the runway and in line with it, to aid the pilot in his landing approach during adverse weather conditions.

The ice thickness should be checked at different points once a week when air temperatures are below 10°F, twice a week when they are between 10 and 25°F, and daily when above 25°F, or less frequently when ice thickness substantially exceeds requirements. A new hole must be drilled for each measurement.

Daily inspection of the runway is necessary, clearing new snowdrifts and observing development of cracks. Cracks over 1 $^1/_2$ inches wide should be healed with slush if possible.

Special attention must be paid to cracks in the parking area. Aircraft may be allowed to roll perpendicularly over single cracks, but should not be parked on a crack. Do not allow aircraft to roll over places where several large cracks intersect. Small flags will help aircraft avoid dangerous spots.

Alternate parking areas should be provided to give the ice an opportunity to heal and regain its strength.

Close parking of several aircraft is permitted only if the ice is very thick. For example, one third more ice thickness is required if two airplanes park very close together. If only the minimum ice thickness is available, loads must be separated by at least the "load-influence distance", which depends on the ice thickness and is given in Table II. Open cracks and even a free ice edge are allowable at this distance from the load, which, however, should move only very slowly.

Pack ice calls for special precautions. Splitting and formation of leads must be closely watched. Only the experienced observer will find early warning signs. Equipment and supplies should be well dispersed to prevent dangerous losses.

In an emergency, personnel and vital equipment can be removed by light aircraft or helicopters. The main concern is for heavier aircraft which might be parked on the ice during splitting. Providing alternate air strips, will reduce this risk. In one case an aircraft was taxied over a small lead on an emergency bridge.

8. Emergency landings and operations under marginal conditions.

Work on criteria for emergency landings, with increased risk to the aircraft for the purpose of saving the crew, was recently done at SIPRE.

The criteria given in Appendix I for emergency landings involve some risk of breakthrough after the aircraft comes to a standstill. They are computed in such a manner that it is still reasonable but risky to utilize the ice runway. Under exceptional emergency conditions it is advisable to use even thinner ice for landings with increased risk. The real danger starts when the ice breaks immediately upon touchdown or while the aircraft still has a high speed.

Under most circumstances, however, it is better to make an emergency landing on ice than on land. Accidents on ice have proved far less serious than corresponding mishaps even on concrete runways. The shock is greatly absorbed by snow and elastic resilience of the ice cover. There are very few cases of breaking through while moving on thin ice. Usually the gear breaks through after coming to a stop, and the aircraft sits on its belly or wings without sinking immediately, giving the crew time to escape. If a landing has to be made on ice which is known to be too thin, the landing gear should be left up.

It is essential for the man in the field to know how failure of the ice cover proceeds and what the danger signs are.

When operating on unsafe ice, the engines must be kept idling. One pilot should remain at the controls and one man should watch the behavior of the ice. Some cracking (often invisible but audible) can always be allowed, although it is a warning. With excessive loading, radial cracks run from one main gear towards the other and then in other directions. In case of skis or tandem wheels, the first cracking will be in the direction of a single ski or tandem wheel assembly. These cracks are hardly noticeable and at best appear on the snow cover as fine lines. But each crack is accompanied by a sharp sound, especially on colder ice. After considerable radial cracking, a circumferential crack forms suddenly several yards away from the main gear, and the airplane sags noticeably. Breakthrough in most cases is not immediate, but will certainly occur unless the aircraft is moved a distance at least equal to the load-influence radius (Table II). Thus it is possible to unload an aircraft under marginal conditions by frequent moving before circumferential cracks occur. Cracking is more audible in fresh-water ice than in sea ice.

If the aircraft breaks through, the ice will fail very close to the main wheels. The surrounding ice will crack but not fail completely.

It is good general practice, even on safer ice, to unload the aircraft rapidly and avoid prolonged parking.

9. Some rules for forecasting ice thickness.

A simple equation for forecasting ice thickness has already been given. In addition, operational needs will frequently require forecasts of the usefulness of a given site for heavier aircraft or increased traffic.

Growth of the ice cover can be accelerated by snow removal, as mentioned above. In some cases, however, a site will merely be visited by a survey party with no snow-removal equipment.

In that case, the best guess will be obtained by applying the following equation:

$$\Delta t = \frac{\beta(1+h_i)}{32-F} \qquad (3)$$

Δt — time necessary for ice thickness to increase by an increment of 2 inches
h_i — measured or estimated ice thickness, inches
F — average expected air temperature, °F.
β — coefficient (values given in Table I).

Example: It is proposed to utilize a given lake. An advance survey party measures an ice thickness of 16 in. The aircraft requires 22 in. The expected mean air temperature is 12°F and $\beta = 8$.

We apply Equation 3 as follows:

From 16 to 18 in. $\Delta t = \frac{8(1+16)}{32-12} = 6.8$ days.

From 18 to 20 in. $\Delta t = \frac{8(1+18)}{20} = 7.6$ days.

From 20 to 22 in. $\Delta t = \frac{8(1+20)}{20} = 8.4$ days.

total $\cong$ 23 days.

Thus the forecast is that, in 3 weeks, safe landings can be made on this lake. The actual length of time necessary for a given increase in ice thickness depends very much on the depth and type of snow.

If information on the depth of the snow cover is available, the following equation can be used:

$$\Delta t = \frac{3.6(1+h_i+rh_s)}{\alpha_1^2(32-F)} \qquad (4)$$

r — equivalent ice thickness giving the same insulation as 1 inch of snow. See Table V for these values
h_s — average expected snow depth, inches
α_1^2 — coefficient, depending on velocity of stream flow and degree of sheltering of the water body from wind (Table VI).

Table VI. Values of α^2 in Equation (4).

α_1^2	Condition
1	for ideal conditions, an open windswept lake
0.80	sheltered lake
0.75	open river with moderate flow
0.60	sheltered river with moderate flow
0.30	open river with rapid flow
0.25	sheltered river with rapid flow.

Example: 26 in. of ice was measured on a slightly sheltered lake; 32 in. is necessary for the contemplated landing. The snow cover is 3 in. and expected to increase to 4 in. Average expected temperature is 0°F. $\alpha_1^2 = 0.90$ and $r = 12$, according to Table V. The necessary time is:

From 26 to 28 in. $\Delta t = \frac{3.6(1+26+12x4)}{0.90\ 32-0} = 9.4$ days.

From 28 to 30 in. $\Delta t = \frac{3.6(1+28+12x4)}{0.90x32} = 9.6$ days.

From 30 to 32 in. $\Delta t = \frac{3.6(1+30+12x4)}{0.90x32} = 9.9$ days.

Total $\cong$ 29 days.

Faster freezing can be achieved by compacting the snow to 2 in. with a density of 0.50 ($r = 3$).

In that case the required time is:

from 26 to 28 in. $\Delta t = \frac{3.6(1+26+3 \times 2)}{0.90 \times 32} = 4.1$ days.

Repeating this calculation for the other increments, the total will be $4.1 + 4.4 + 4.6 \cong 13$ days. Operations can begin 2 weeks earlier.

The computed values can be only approximate since the growth of ice depends on a number of factors which cannot be accounted for without special investigations. Equation (4) cannot be applied if slush forms on top of the ice cover.

10. Ice airfield journal.

This journal is a document covering the establishment and maintenance of an airstrip on ice. It must be written and signed by a specially designated person, responsible for proper maintenance of the runway and delivery of messages on its condition. Experience has shown that, unless a designated person is responsible, maintenance is poor.

The ice airfield journal should contain the following data:

a) Date and result of exploratory survey with sketch of general situation, cracks, pressure ridges, etc. Note whether on sea ice in bay, pack ice, lake or river ice.

b) Date and procedure of first and all subsequent snow removals.

c) Height of snow on runway, loose or dense, height of snowpiles.

d) Current data on ice thickness - noting total ice thickness, depth at which sea ice changes from light to dark color, depth at which snow ice (if any) changes to black, transparent fresh-water ice, ice surface temperature under the snow on the runway, and depth of water.

e) Description of crack development - noting width (and approximate depth) of dry and wet cracks. Date and details of artificial healing.

f) Daily air temperatures. Thermometer must be located in shade. Daily mean can be derived from the following combinations: mean of maximum and minimum; or mean of measurements at 7, 13, and 21 hr. local time; or mean of measurements at 0:30, 6:30, 12:30 and 18:30 Zebra time. The last combination is preferable, since weather observations for aviation purposes are taken at these times.

g) Landing and parking record. Type of aircraft, gross weight, time of landing, duration of parking on the same spot. Record of cracking.

Describe in detail whether cracking under aircraft was heard or seen during taxiing or parking; note whether cracking was occasional or frequent; describe whether sagging was observed. Any incidents or unusual occurrences, especially during emergency landings, should be entered in detail.

h) During thawing weather the depth of slush on the ice must be noted, as well as the formation of pit holes.

i) Deflection record under or at aircraft if such observations were made by engineer's level. Note the place of the rod in relation to aircraft.

Radio all essential information to main base.

It is requested that a copy of the airfield journal be sent to the Snow Ice and Permafrost Research Establishment, 1215 Washington Avenue, Wilmette, Illinois, after completion of the operation. Such records are necessary for technical evaluation and continuing improvement of use of ice for airfields.

SIPRE Table of Ice Thicknesses
for Landing of Aircraft

Note: Work on the problem and further tests are continuously in progress with resulting improvement of operational criteria. Request latest edition of the SIPRE table or information for specific aircraft before major applications or reproduction in other publications.

SIPRE Table for emergency and safe landing of selected aircraft on fresh-water ice and sea ice

Issue: January 1956

(Numbers in parentheses refer to Remarks)

Type	Gear	Assumed gross weight, lb (6, 7)	Take off run, ft (1)	Fresh-water ice (11) thickness, inch						Sea ice thickness, inch					
				Emergency operation (2)			Regular operation (8)			Emergency operation (2)			Regular operation (8)		
				Air temperature, °F (3, 4)						Air temperature, °F (3, 4)					
				14	22	31	14	22	31	10	19	28	10	19	28
C-47 D	wheels	29,000	2900	$12^1/_2$	$13^1/_2$	16	$17^1/_2$	$19^1/_2$	22	$19^1/_2$	22	26	26	30	35
C-47 D	skis	30,500	—	11	12	14	$15^1/_2$	17	$19^1/_2$	$17^1/_2$	20	24	23	27	32
C-54 G	wheels	67,500	2780	$17^1/_2$	$19^1/_2$	22	25	28	32	26	30	36	36	41	49
C-119 B	wheels	61,800	2450	16	$17^1/_2$	21	22	25	28	25	28	34	34	37	45
C-124 A	wheels	168,000	5220	28	32	36	40	45	51	40	46	54	54	62	74
SA-16	wheels	31,400	—	13	$14^1/_2$	$16^1/_2$	$16^1/_2$	$18^1/_2$	21	21	24	29	28	32	38
SA-16	skis	31,400	—	$13^1/_2$	15	17	$18^1/_2$	21	24	21	24	29	28	32	38
DHC-3	wheels	6,540	—				Not computed yet						$13^1/_2$	14	$15^1/_2$
DHC-3	skis	6,870	—				Not computed yet						$11^1/_2$	$12^1/_2$	$13^1/_2$

Note: Do not use or reproduce this table without the remarks on the following pages.

Remarks concerning table for landing of aircraft on ice:

1. Takeoff run is given for standard conditions: maximum gross weight sea level and 59°F air temperature. This is not the required runway length, which must be decided by the operations.

2. Figures given for emergency landings involve some risk of breakthrough (of landing gear only: aircraft will not sink). Move aircraft around on ice or, better, remove it from the ice as soon as possible.

3. Air temperature is the average over the following number of days:

Ice thickness, inches:	below 20	20 to 40	above 40
Number of days:	3	4	5

4. If operations have to proceed under average air temperatures higher than 31°F on fresh water ice, and higher than 28°F on sea ice, the required ice thickness, given under these columns, have to be gradually increased by up to 20% more, until deterioration of surface conditions (slush or candling) prevents further operations. In any case, suspend operations if maximum air temperature exceeds 40°F.

5. The recommended ice thicknesses are not in a simple relation to the gross weight, since gear configuration is also considered.

6. Gross weight is given as normally expected for operations on ice. For C-47 and other ski-equipped aircraft a 5% weight allowance was made for ski and additional fuel.

7. If weight exceeds indicated gross weight, add 6% to ice thickness for 10% weight increase.

If weight is less than indicated, 5% ice thickness may be deducted for 10% less weight.

8. Parking up to 1 hr under regular operations. Increase required thickness by 25% for 24-hr parking and move aircraft daily under low temperature conditions (below 10°F for sea ice, or 14°F for fresh-water ice). Under medium temperature (19° or 22°F) only 6 hr-parking is allowed with 25% more thickness than required by table. Consider remarks 4, 7, and 9. Under higher temperature (28° or 31°F), prolonged parking beyond 1 hr is not recommended, unless the ice thickness substantially exceeds requirements.

9. Increase required ice thickness by 10% for dry cracks (width often about $1^1/_2$ inches) and by one third for wet active cracks over $2^1/_2$ inches wide. Disregard hair cracks.

10. It is assumed that snow is removed, except for 2-3 inches. Greater ice thickness is recommended when covered by deep snow or when used less than 2 days after removal of deep snow. Wheeled aircraft should not land on uncompacted snow deeper than $^1/_3$ of the wheel diameter.

11. Sometimes white snow-ice (frozen slush) with round air bubbles will be found on top of transparent black fresh-water ice (rarely on sea ice). Count only half of the snow ice in the effective thickness. Example: 8 inches black ice, 10 inches snow ice: effective thickness

$$8 + \frac{10}{2} = 13 \text{ inches.}$$ A C-47 for instance, is allowed to land here only under emergency conditions.

12. Occasional cracking should not lead to concern. Use two parking places alternately. If cracking is frequent, use two alternate airstrips. Suspend operations if noticeable sagging is observed.